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ABSTRACT

This course in electronic devices and systems is one of 16 courses in the Energy Technology Series developed for an Energy Conservation-and-Use Technology curriculum. Intended for use in two-year postsecondary technical institutions to prepare technicians for employment, the courses are also useful in industry for updating employees in company-sponsored training programs. Comprised of seven modules, the course is designed to provide the student with a working knowledge of modern electronic devices and the circuits in which they are employed. Electronic troubleshooting techniques are stressed. Topics covered include rectifiers, transistors, SCRs and triacs, vacuum and gaseous tubes, filters, amplifier circuits, operational amplifiers, noise reduction, digital circuits, and display devices. Written by a technical expert and approved by industry representatives, each module contains the following elements: introduction, prerequisites, objectives, subject matter, exercises, laboratory materials, laboratory procedures (experiment section for hands-on portion), data tables (included in most basic courses to help students learn to collect or organize data), references, and glossary. Module titles are Concepts and Applications of Input and Output, Vacuum Tubes, Solid State Devices, Integrated Circuits, Indicators and Displays, Digital Techniques, and Analog and Digital Systems. (YLB)

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ED210511

ELECTRONIC DEVICES

AND SYSTEMS

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PREFACE

ABOUT ENERGY TECHNOLOGY MODULES

The modules were developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment and are useful in industry for updating employees in company-sponsored training programs. The principles, techniques and skills taught in the modules, based on tasks that energy technicians perform, were obtained from a nationwide advisory committee of employers of energy technicians. Each module was written by a technical expert and approved by representatives from industry.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Laboratory Materials, which identify the equipment required to complete the laboratory procedure.

Laboratory Procedures, which is the experiment section, or "hands-on" portion, of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

References, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the prestated objectives.

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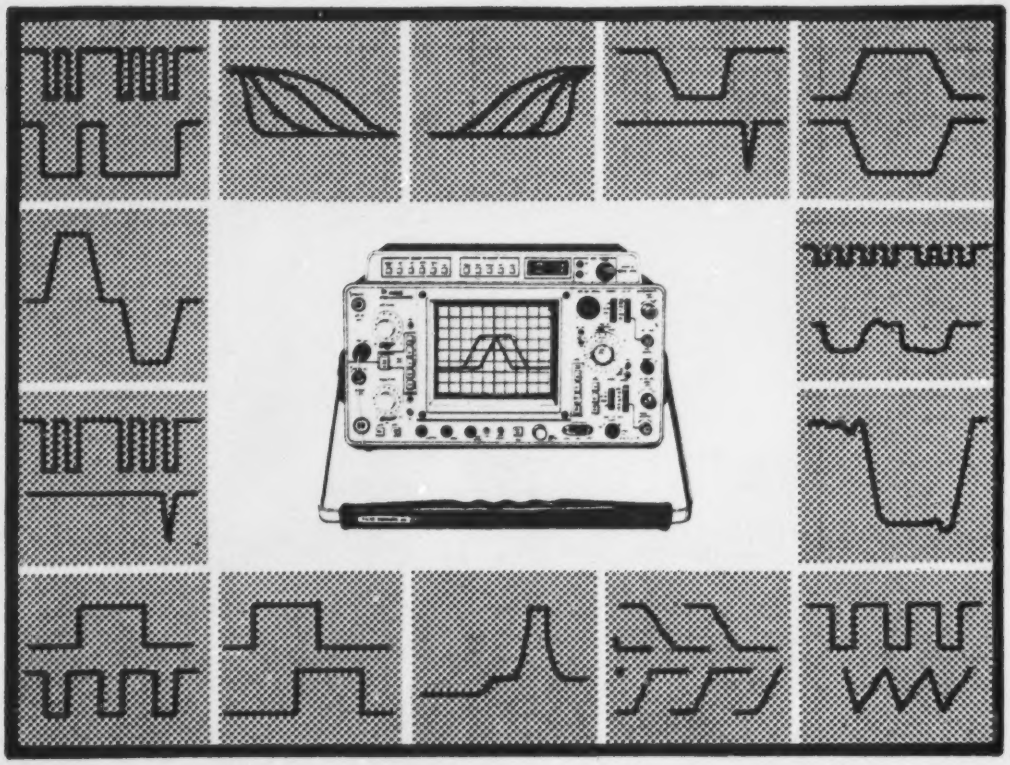
ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-01

CONCEPTS AND APPLICATION
OF INPUT AND OUTPUT

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INTRODUCTION

Since understanding basic building blocks of electronic equipment is imperative to functioning effectively in electronics and associated fields, this module covers general applications of stages and systems. The discussion includes flow of signals through stages and systems, and voltages necessary for operation.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define a stage.
2. Define a system.
3. Explain what a signal is, and how a signal can be changed.
4. Define input to a stage.
5. Define output from a stage.
6. State the purpose of an amplifier.
7. State the purpose of wave-generation stages.
8. Name the types of waveshaping stages and what they do.
9. List the three stages of a power supply and what jobs these stages perform.

10. Identify indicator devices and state their characteristics.
11. State the purpose of silicon-controlled rectifiers (SCRs) and Triacs.
12. Name the two main categories of digital circuits and describe their purpose.

CONCEPTS AND APPLICATION OF INPUT AND OUTPUT

Electronic devices such as transistors, integrated packages, capacitors, inductors, transformers, and resistors are interconnected to create electronic stages and systems. Various arrangements are employed in electronics. A stage is defined as "a section in electronic equipment that performs an individual, specific task." A system incorporates several stages and performs many tasks.

In virtually all stages and systems, "input" and "output" are electrical locations that accept and pass on that which is applied to the stage or system. That which is applied to a stage or system is called a signal, and is usually a voltage representation. All stages or systems modify the applied signal. The pages that follow discuss stage and system applications, as well as modifications they perform on signals.

APPLICATIONS OF STAGES AND SYSTEMS

The many stages and systems in use have much in common. In any stage or system, the following variables applied to the input can be altered:

- Voltage.
- Current.
- Power.
- Frequency.

Voltage is electrical pressure that causes electrons (current) to move through a circuit.

Current is the movement of electrons through a circuit.

Power is the amount of electrical work being done in a given time period.

Frequency is the rate at which a given alternating current changes. The speed at which current reverses direction is associated with current frequency.

In many cases, only one variable will be changed. In other cases, two or more variables can be altered. The following are some changes that can be performed:

- Amplitude.
- Shape.
- Inversion.

Amplitude refers to the amount of a given value. Five volts is indicated as an amplitude of 5 volts. A value such as 0.16 amperes is also an amplitude – in this case, of current.

Shape is a pictorial representation of amplitude changes in a given time period.

Inversion refers to a signal that is turned upside down, or inverted. Amplitude and frequency are not affected.

Examples are depicted in Figure 1. Figures 1a and 1b show a voltage increase taking place. The signal in Figure 1a is not inverted; in Figure 1b it is. Figure 1b also shows an increase in signal amplitude, as does Figure 1a. Figure 1c shows a shape change with no amplification or inversion. Figure 1d shows a shape change and amplification.

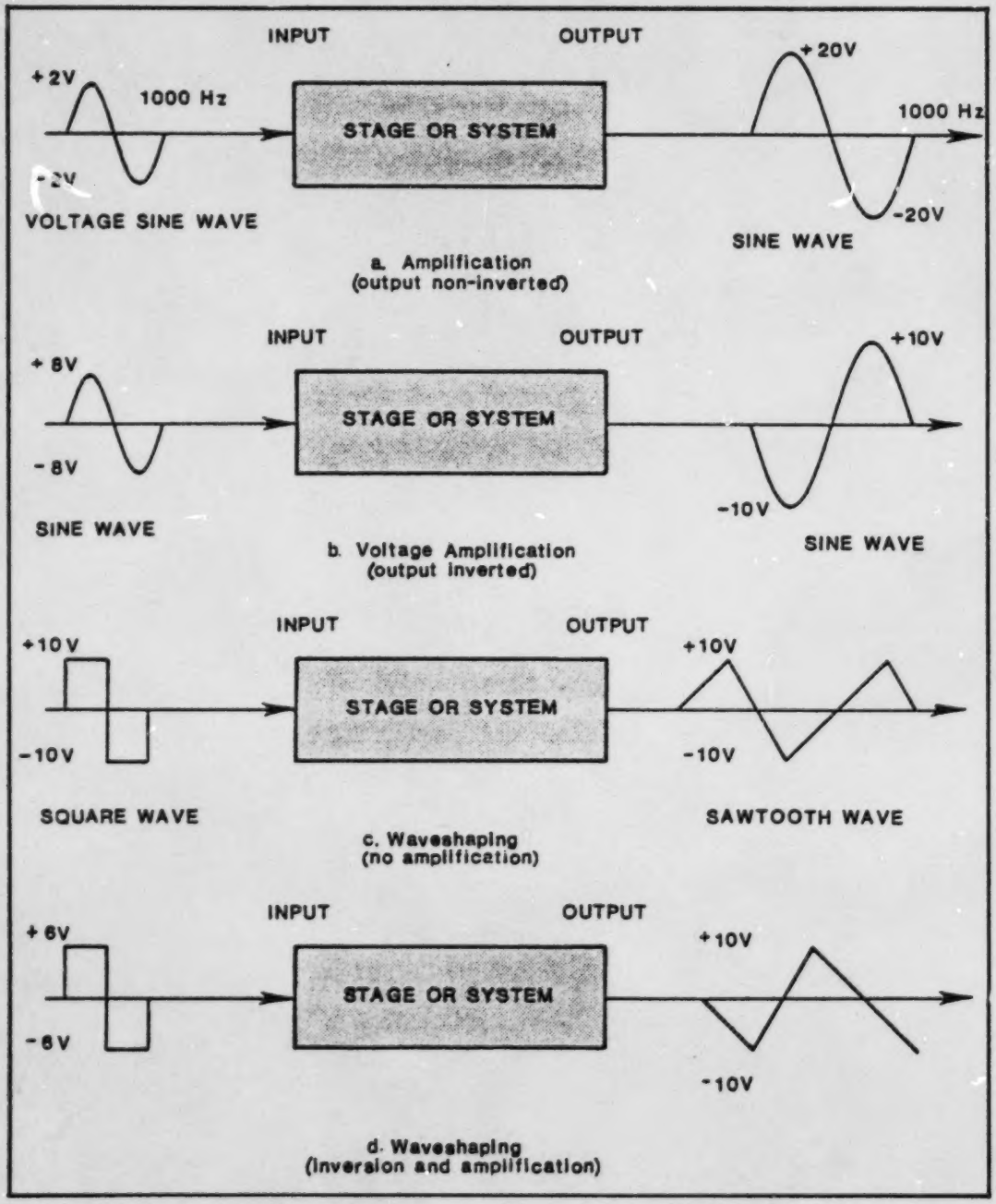


Figure 1. Examples of Stage Application.

Regardless of the number of changes, almost all stages or systems can be classified by the specific change or changes they perform. The following categories summarize most electronic applications:

- Amplifier (amplification).
- Oscillators and wave generators.
- Waveshaping.
- Rectifiers and filtering.
- Regulators.
- Indicators and displays.
- Thyristors (electronically-controlled switches).
- Digital.

Decision-making stages or systems are advancing rapidly in most applications, and the most common is the amplifier. In this module, each of these items is discussed as a general application. Practical examples are used for emphasis. Unless otherwise stated, examples shown refer to a stage. Later modules discuss each application in detail.

AMPLIFIERS

An amplifier is a stage that increases the level or amount of one or more of the following values:

- Voltage.
- Current.
- Power.

Amplifiers are essential in most electronic equipment. Figure 2 shows some uses for these stages. The amplifier can amplify all or part of the signal applied to the input.

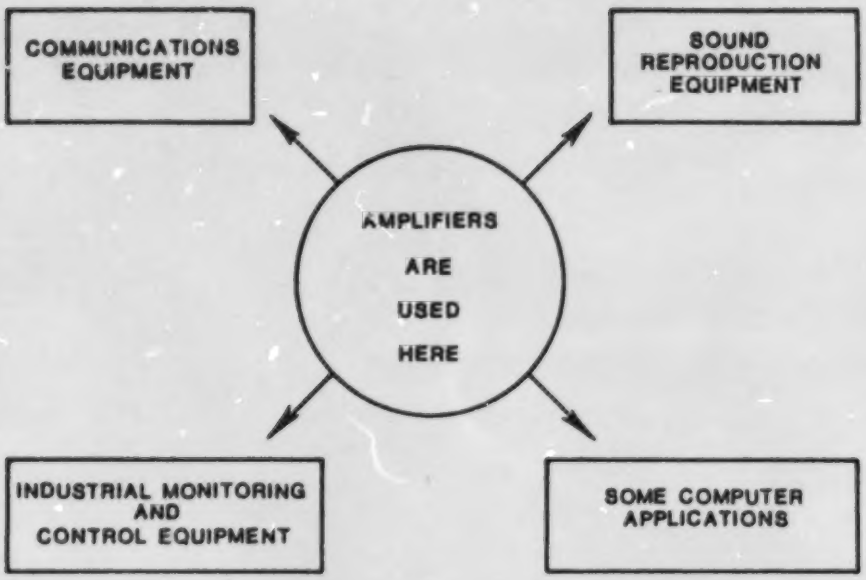


Figure 2. General Amplifier Use Categories.

When a stage acts as an amplifier, it is called an analog stage. The term "analog" indicates that the amplifier looks at all the input signal and can, if necessary, reproduce it completely.

Most amplifiers are either voltage or power amplifiers. These two classifications can be subdivided into two categories which also have divisions, as seen in the following breakdown:

DIVISIONS

1. Class of operation identifies how much of the input signal will be amplified and passed on to the output of a stage. The classes are as follows:
   a. Class A.
   b. Class B.
   c. Class AB.
   d. Class C.

SUBDIVISIONS

2. Frequency of operation identifies the operation rate of the amplifier. Different input signals to amplifiers are at different rates of operation. An amplifier must be designed to accommodate a specific frequency rate.
   a. D.C. amplifiers.
   b. A.C. amplifiers.
      (1) Audio frequencies (AF).
      (2) Video frequencies (VF).
      (3) Intermediate frequencies (IF).
      (4) Radio frequencies (RF).

The major difference between the four classes of operation (A, B, AB and C) is accuracy of reproduction. Class A reproduces most accurately, with possible error less than 1% to 2%. In Class C operation, however, over 50% of the signal is destroyed when it passes through the stage – but some of the lost signal is recaptured at the output by using a reinsertion process.

The subdivision "frequency of operation" is more obvious. The input signal frequency may be zero, as is the input to a d.c. amplifier, or it may be in the upper ranges of a.c. frequencies. As signals reach radio frequencies, a peculiar phenomenon occurs. Instead of traveling in wires, signals radiate into the atmosphere and travel great distances.

This text will not attempt to break frequency of operations classifications into other possible subdivision.

Figure 3 shows a few specific applications for amplifiers.

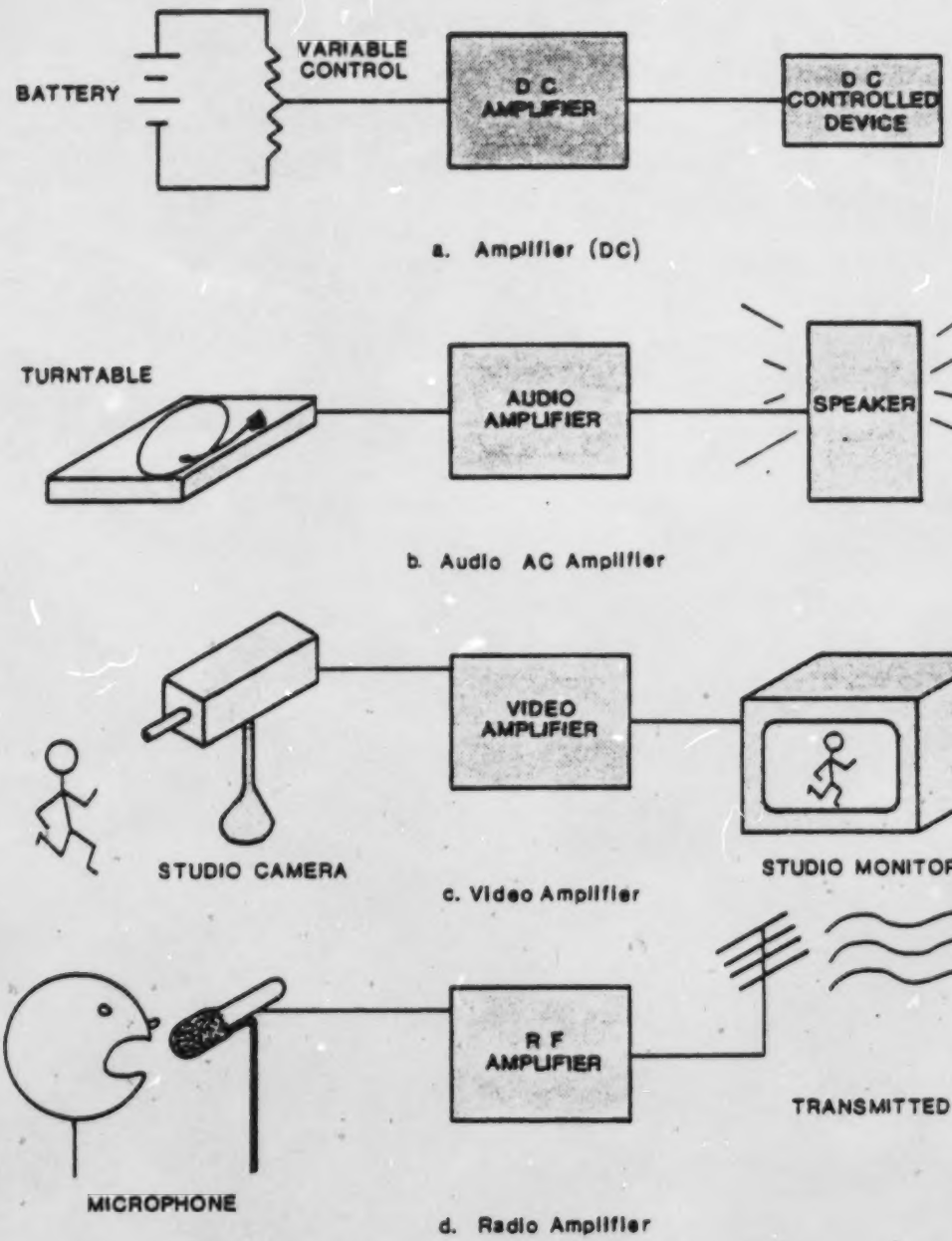


Figure 3. Specific Amplifier Uses.

OSCILLATORS AND WAVE GENERATORS

OSCILLATORS

Oscillators and wave generators are used in several electronic applications. Among these are organs, communications equipment, industrial control equipment, computers, electronic watches, and navigation applications.

These stages are required for the production of a reference to which signals are compared, added, or subtracted. The terms "oscillator" or "wave generator" refer to a replica or repetition. The beat of the human heart is an analogy, since each heartbeat is dictated by the exertion requirements for certain activities. Likewise, an oscillator or timer can be changed by altering part of the stage. Each application indicates a particular required rate.

Oscillators and wave generators serve similar roles. Both produce a repeated wave that supplies a signal to other system parts. Oscillators and wave generators are usually categorized by the stage part (or parts) that determines the rate of operation. In an oscillator, these parts are as follows:

- Resistor-capacitor (RC).
- Inductor capacitor (LC).
- Crystal.

RC oscillators are used in the audio frequency ranges. They consist of a resistor and capacitor combination (called an RC time constant) that establishes the required frequency.

LC oscillators use coils and capacitors to determine the rate of operation. This is accomplished by using the

resonant frequency principle of placing a coil and capacitor in series (or parallel with each other) at the input of the stage.

Crystal oscillators generate a given rate of operation by the use of a stone crystal. Voltage is applied to the crystal, causing current to flow in the crystal. As a result, this device will continue to vibrate at a precise rate as long as voltage is applied. As with RC and LC oscillators, the crystal is placed in the input to the stage.

All oscillators employ a principle called feedback. To generate a repeating signal from the stage, a part of the signal is fed back from the output to the input, so that the output supports the input signal. As a result, repetition is guaranteed. An example of this principle is shown in Figure 4.

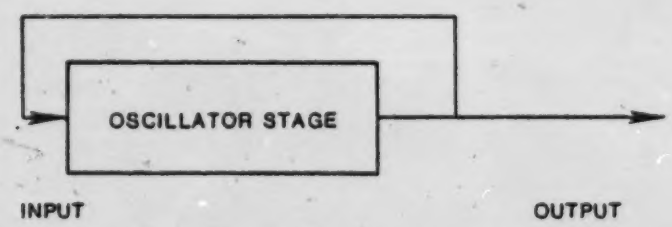


Figure 4. Oscillator Stage (Showing Feedback).

It should be noted from Figure 4 that an oscillator stage has no input from a preceding stage. In this application, the rate-determining network is placed in the input to create the original signal for repetition; a portion of the rate-determining network's signal is fed back from the output. A continuous signal is then available from the output that is used as a signal provider for another stage.

In summary, oscillators must meet four requirements, as follows:

1. Must be self-starting.
2. Must provide positive feedback.
3. Must be capable of rate determination.
4. Output must replace input losses.

These requirements will be discussed in a later module.

The output of RC, LC, and crystal oscillators is in the shape of a sine wave, as shown in Figure 5. Although the amplitude may vary from oscillator to oscillator, the shape from a given oscillator is unchanging.

Figure 5. Sinusoidal Waveshape (RC, LC, and Crystal Generation Outputs).

WAVE GENERATORS

Wave generators are stages whose outputs are used as system-timing signals. Timing signals resemble the heartbeat or a ticking clock. Without the timing signal, there is no operation in a system that uses a wave generator. Wave generators differ from oscillators primarily in the shape of the wave they produce. The most common wave generators are the following:

1. Rectangular or square wave generators.
2. Ramp generators.
   a. Sawtooth.
   b. Trapezoid.
   c. Triangle.

There are several types of wave generators, but rectangular wave generators are used most often. Other waveshapes are developed easily from the rectangular shape. The rectangular wave can be developed by this generator in one of the following three ways, depending upon the required application:

1. Astable (free running).
2. Monostable (one stable state).
3. Bistable (two stable states).

Astable

Astable, or free-running generators, output a continuous rectangular series of pulses, as described in Figure 6. A pulse is a repeated amplitude change in a given time period that is determined by the frequency of the oscillator. Astable generators do not remain in a stable state, as do monostable or bistable types.

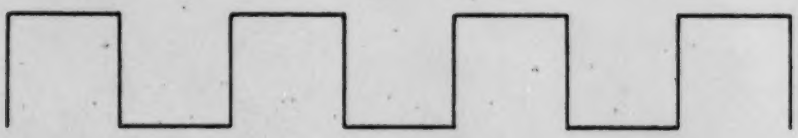


Figure 6. Astable Waveform.

With the use of capacitors, coils, and resistors, sawtooth and triangular waves can be developed from the output of the wave generator.

Monostable

The monostable generator has only one stable state. It requires an external trigger signal to change momentarily from its stable state to a temporary state and back again. The shapes of its output and trigger signals are shown in Figure 7.

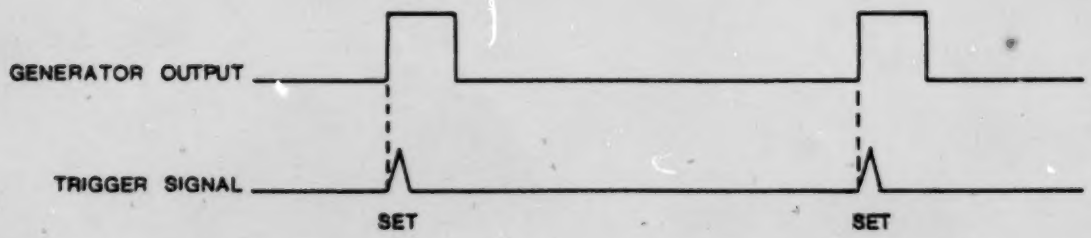


Figure 7. Monostable Waveshape (With Triggering Pulse).

Bistable

A bistable generator has two stable states. Two external trigger pulses flip the generator back and forth from one state to another as trigger signals occur. As in the monostable generator, the stage's state only changes when a trigger signal provides impetus. Note the difference between the monostable generator waveshape in Figure 7 and the bistable generator waveshape in Figure 8.

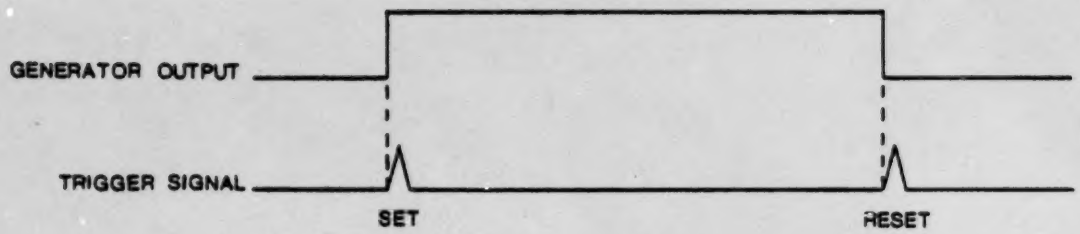


Figure 8. Bistable Waveshape (With Triggering Pulse).

One wave generator is the Advanced 555 Timer, a small, inexpensive case containing the stage in a sealed housing.

The timer acts as a monostable or an astable generator — whichever is required. Moreover, the output rate can be easily adjusted from less than one second to several hours. Bistable timers are discussed at length in a later module.

RAMP GENERATORS

Ramp generators are used in oscilloscopes, radar, television, and computer television monitors. This waveform causes the picture image to be traced across the face of the screen. Of particular importance is the linear shape in which the wave occurs. A brief example of shape and use is illustrated in Figure 9.

Oscillators (RC, LC, and crystal) have an output signal called sinusoidal. A sinusoidal wave has the same shape as a wave produced from the alternating current generator in the power station. Wave generators, on the other hand, produce a nonsinusoidal wave (a shape other than sinusoidal). This shape takes many forms.

Shape - Triangular

Application - Digital Voltmeters and Analog to Digital Convertors

Shape - Sawtooth

Application - Radar and Television

Shape - Sawtooth

Application - Oscilloscopes

Figure 9. Nonsinusoidal Waveshapes.

WAVESHAPING

Many applications in electronics require a waveshape other than those discussed so far. Furthermore, when a rectangular, sawtooth, or triangular wave is required, some

minor changes can occur because of design methods, and necessary restoration of the original wave is required. Waveshaping stages or circuits are used to perform these tasks.

The following categories of waveshaping circuits will be discussed briefly (using block diagrams and signal flow):

1. Integrator RC shaping (resistor-capacitor).
2. Differentiator RC shaping (resistor-capacitor).
   a. Clippers.
   b. Slicers.

Notice that the input's shape is changed as a result of the stage used. The output will usually have the same frequency, however.

INTEGRATOR

An integrator stage converts a rectangular wave to a modified sawtooth wave. Figure 10 illustrates the conversion. State components are the use of a resistor and capacitor.

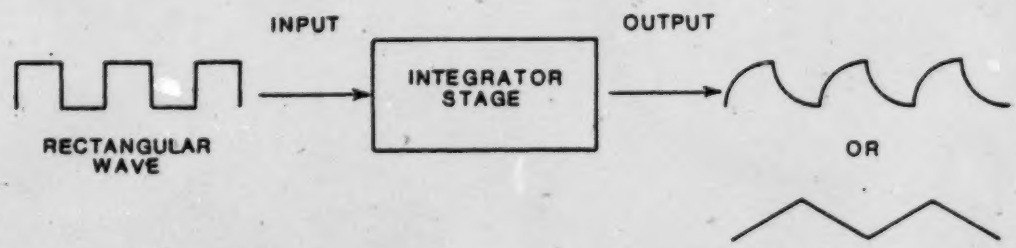


Figure 10. Integrator Stage Conversion.

The rate of repetition does not change as a result; however, shape is altered. Notice that one of two output shapes is possible, depending upon application. This stage is used primarily for waveshape correction. It eliminates distortion created by poor design or component aging.

DIFFERENTIATOR

A differentiator stage is designed to alter a sine wave without destroying its shape. However, the differentiator stage usually does alter the amount of signal, as well as signal starting time. This condition is illustrated in Figure 11.

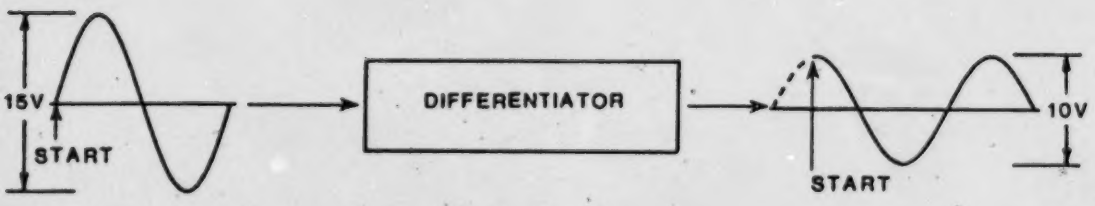


Figure 11. Differentiator Stage.

Although the basic shape is still sinusoidal, start time and height have been changed. Differentiators can also be used to alter other waves. Figure 12 shows the square wave being changed. Note the output wave is now a spike. This shape can be used to trigger the wave generators previously discussed. Another name for trigger pulse is steering pulse.

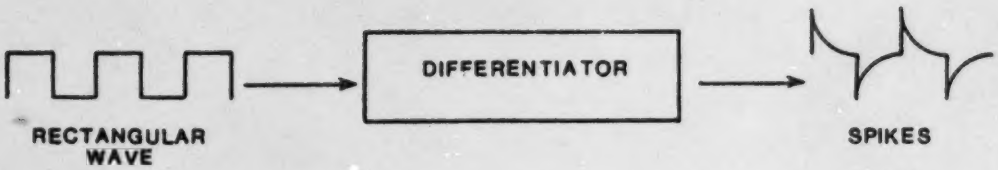


Figure 12. Other Differentiator Applications.

CLIPPERS

A clipper stage is designed to cut off an unwanted portion of a wave. Noise pulses – often produced by interference from motor brushes, power line insulators, internal electronic equipment noises, automobiles and trucks – must be eliminated if a stage or system is to operate properly.

Clippers are of two types: a series clipper and the parallel or shunt clipper. Clipper names describe the way they are constructed electrically. Clipper output waveshapes are illustrated in Figure 13. Figure 13 illustrates two possible outputs. While the circuit has to be altered to produce one output or the other, the input signal is the same for both.

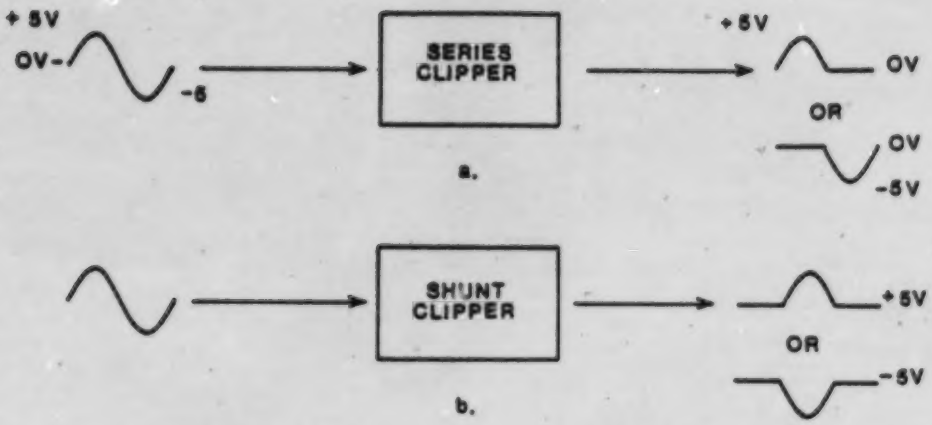


Figure 13. Clipper Stages.

SLICERS

A slicer stage (Figure 14) serves a similar purpose. The center portion of the input wave is retained; whereas, the top and bottom parts of the input wave are cut off. This stage is placed in a system prior to a stage requiring constant amplitude or level. In the slicer(s), the input wave rate is unchanged.

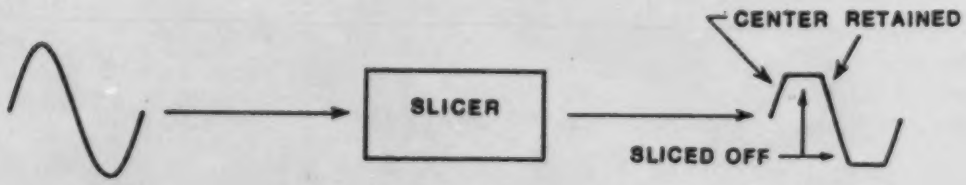


Figure 14. Slicer Stage.

Several input signals can be applied to the slicer (one at a time). In each case, the output will have the top and bottom removed.

RECTIFICATION AND FILTERING

All electronic equipment requires direct current voltages to provide proper conditions for operation. Like the automobile engine moves the car forward or backwards only when the driver performs the proper operations, so it is with electronic equipment. The power supply in which rectification takes place provides idle voltages for the system. When the signal is applied to the input, the direct current voltage becomes the means by which the signal travels through and reaches the output.

It is imperative that stage-operating voltages be direct current voltages. When applied to a stage, voltages become a reference for the signal. If voltages are alternating current voltages, the reference is variable and of little value. Alternating current voltages must be changed to direct current voltages.

Most electronic equipment receives initial voltages from alternating current – usually 120 volts a.c. This, of course, is obtained from a wall outlet. Because it is a.c., the current must be converted to d.c. to be used as reference voltage in electronic stages and systems. The rectifier is the stage that provides initial conversion. Further changing of the voltage wave is required to assure direct current.

The filter stage provides the final change. A filter stage consists of resistors, capacitors, and sometimes, a coil to complete the job. Because the graphic representation of a d.c. voltage is a straight line, the results of rectifier and filter action are shown as an approximate straight line. Figure 15 illustrates the input and output of these two stages.

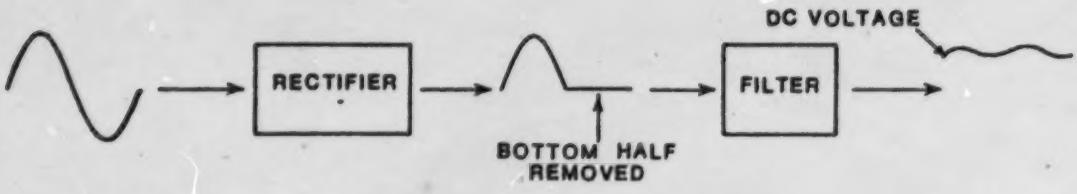


Figure 15. Power Supply Stages.

Although this block stage sequence shows only one type of rectification and filtering, it serves to describe the action taking place.

Rectifiers are generally classified as half wave, full wave, or bridges. This module will not discuss rectifiers in detail. However, generally speaking, half wave rectifiers are the least efficient, and bridged rectifiers are the most efficient.

Filters (the second stage in Figure 15) are also categorized by their efficiency. The two general types are RC filters and LC filters.

The student should note at this point that, although oscillators also possess RC and LC stages, application is not the same. This condition will become more understandable in later modules.

RC and LC filters are used to reduce the a.c. changes from the rectifier to a straight-line voltage. While all variations usually are not removed, filter stages do remove enough variations to accomplish a smooth output voltage similar to pure direct current.

REGULATORS

Voltages provided from power supplies must remain constant in voltage output. In power supplies, the stage that assures constant output is the regulator. A regulator compensates for voltage fluctuations maintaining a constant d.c. voltage at its output. In recent years, power supply regulators have been improved. Recent developments have yielded the solid state regulator. This device is enclosed in a plastic case, with only connections brought to the outside.

Other regulators incorporate the Zener diode, a device that possesses unusual characteristics. As a voltage is applied to this device, the Zener diode allows only a certain voltage to exist. As the input to this stage changes – due to other stage interaction and power line variations – the Zener regulator locks in a preset voltage at its output. These devices can regulate voltages from 2 volts to slightly over 200 volts.

Figure 16 illustrates regulator action and shows connections to the rectifier and filter circuit.

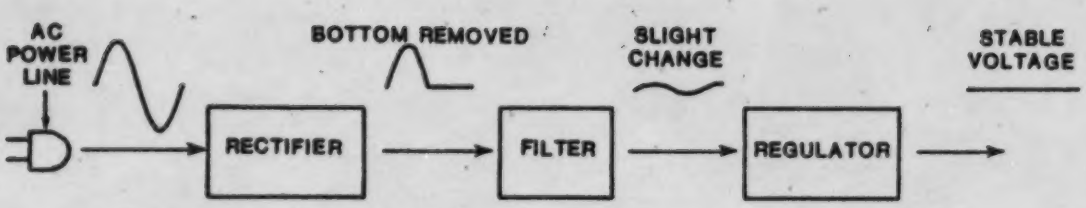


Figure 16. Power Supply With Regulator.

Although power supply protection circuits have not been discussed, all power supplies should have protection. When the system to which power supplies are connected demands more power than the design can handle, smoke – and possibly fire – may occur. Thus, devices such as fuses, circuit breakers, and over-current limiter stages are employed to assure safe power demand limits. These will be discussed in more detail later.

Not all systems use regulator circuits; however, these circuits are becoming more common in general system design as developments lower the price.

INDICATORS AND DISPLAYS

In many electronic systems, it becomes necessary to provide a read-out of some condition that exists either within the system, or as a result of the function of the system. A variety of devices and associated components have been used as display stages. The following list is a cross-section sample of several in use.

- Incandescent lamp.
- Neon lamp.

- Light-emitting devices (LEDs).
- Liquid crystal devices (LCDs).

Incandescent Lamps

Small light bulbs are used to indicate such messages as ON-OFF, standby, warning, system normal, system malfunction or error, and a variety of other conditions. This device emits light when a current flows through the lamp. Its longevity is limited, however, primarily due to the filament. Although some lamps may last as long as 5000 hours, most do not. A lamp has many uses, but it can convey only small amounts of information. The following three states are possible:

- ON.
- OFF.
- Blinking.

Neon Lamps

Although neon lamps serve applications similar to those of incandescent lamps, they usually will last longer. However, a neon lamp has a poor light level output compared to an incandescent lamp. Typically, these lamps are used as indicator lamps on electronic equipment. Often, neon lamps require a resistor placed in the circuit with them to reduce voltage. Most neon lamps – if used as 110 volt indicators – must have this resistor in the stage.

When these lamps begin to fail, the device starts blinking ON and OFF, even when a continuous voltage is applied. Although this will not cause damage, replacement is advisable if the lamp is an indicator.

Light-Emitting Devices

Two devices emerging as promising light emitting units are LEDs (light-emitting diodes) and LCDs (liquid crystal displays).

LEDs are diodes that give off visible light when current is flowing. They can be manufactured to provide light from one source point or from several points, as required. Figure 17 shows the difference between these two types of LEDs.

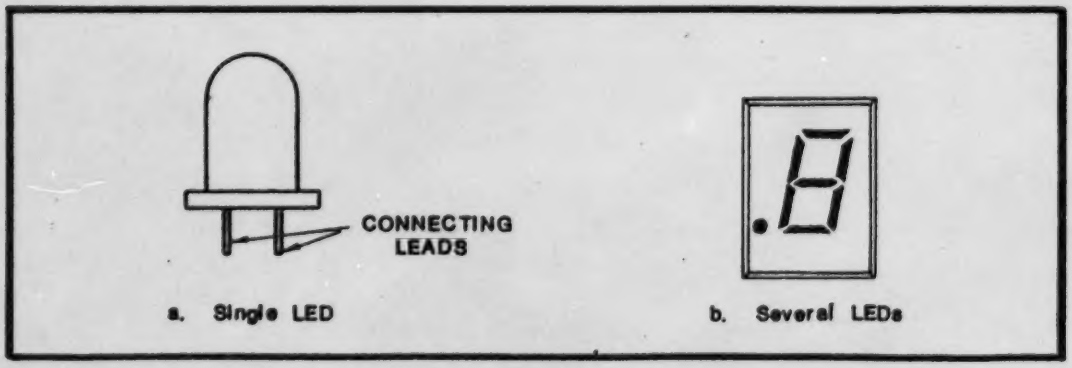


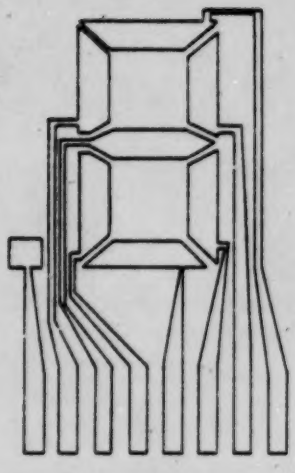
Figure 17. Light-Emitting Diodes (LEDs).

Figure 17a shows a single LED which could be used as an indicator device. These LEDs are available commercially in green, yellow, orange, and red.

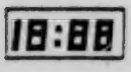
Figure 17b shows seven LEDs combined in one small case to create the 0-9 segment display. All seven segments will be operated for the digit 8 , as shown. If the digit zero is required, only six segments will be operated. LED devices and displays require a small voltage to operate. Light level greater than neons, but less than incandescents, is possible. The LED usually will outlast both incandescent or neon lamps. The power input requirement ranges from near zero watts to about 150 milliwatts, with a life expectancy of, or greater than, 100,000 hours.

LCD displays serve the same purpose as LED displays. They, too, are a 0-9 segment display. One of the major differences between the LCD and LED displays is the power required for operation. LCDs typically require microwatts to operate, as compared to milliwatts for LEDs. Figure 18 shows a typical LCD display. These devices come in two styles: reflective and transmissive (Figure 18). Details of these styles are discussed in a later module.

Proper voltages are inputed to the display stage when a particular number is to be displayed. Proper portions of the segment operate to display the number desired. These devices are used in conjunction with many electronic systems. Particular use has appeared in the calculator field, where low drain on batteries is essential.



a. LCD 8-segment Digit Display



b. Reflective Style

c. Transmissive Style

Figure 18. Liquid Crystal Display.

THYRISTORS

Thyristors (electrically-controlled switches) are a family of stages incorporating a device that can be electronically controlled to act as a switch and/or a variable power resistor. Some thyristors have only the ability to turn d.c. or a.c. current that flows in a system or stage ON or OFF. Other thyristors can adjust the amount of power applied to items they control. Frequent use of thyristors is taking place in the ever-changing industrial automation environment. For example, large motors can be controlled by thyristors. The most widely-used thyristors are those listed below:

- Silicon-controlled rectifier (SCRs).
- Bidirectional triode thyristor.

SCRs are one-way switches; bidirectional triode thyristors are two-way switches. One-way and two-way refer to the ability to pass current through the SCR or triode thyristor.

In the following paragraphs, each device or stage is discussed in regard to input-output and applications most often encountered.

Silicon-Controlled Rectifier

The silicon-controlled rectifier (SCR) is the most commonly used thyristor. This stage is used primarily as a d.c. electronic switch; in other words, it operates properly when current passes through it in one direction.

Figure 19 illustrates a simple use of the SCR. Current is allowed to flow when the control lead receives a voltage. After the SCR triggers ON, it will continue to operate until the main power switch is opened.

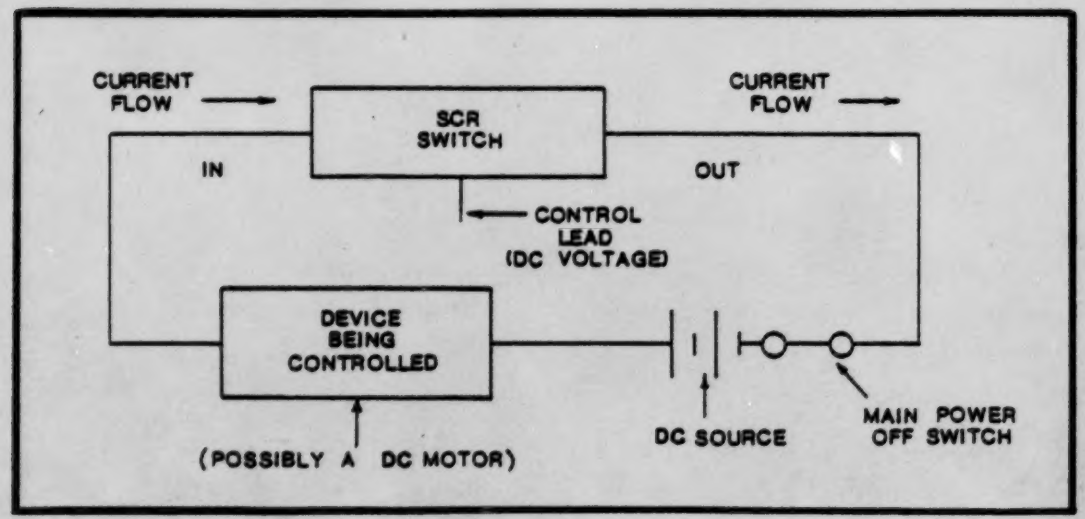


Figure 19. Simple Use of a Silicon-Controlled Rectifier.

SCRs also can be used to control a.c. current flow — as a switch, or as a device to vary the amount of power being fed to a controlled system.

Figure 20 is a block diagram of an application. The SCR closes when the a.c. control voltage appears on the control lead. Once current is flowing through the SCR, it cannot be stopped unless the main switch is opened or current flow is otherwise reduced.

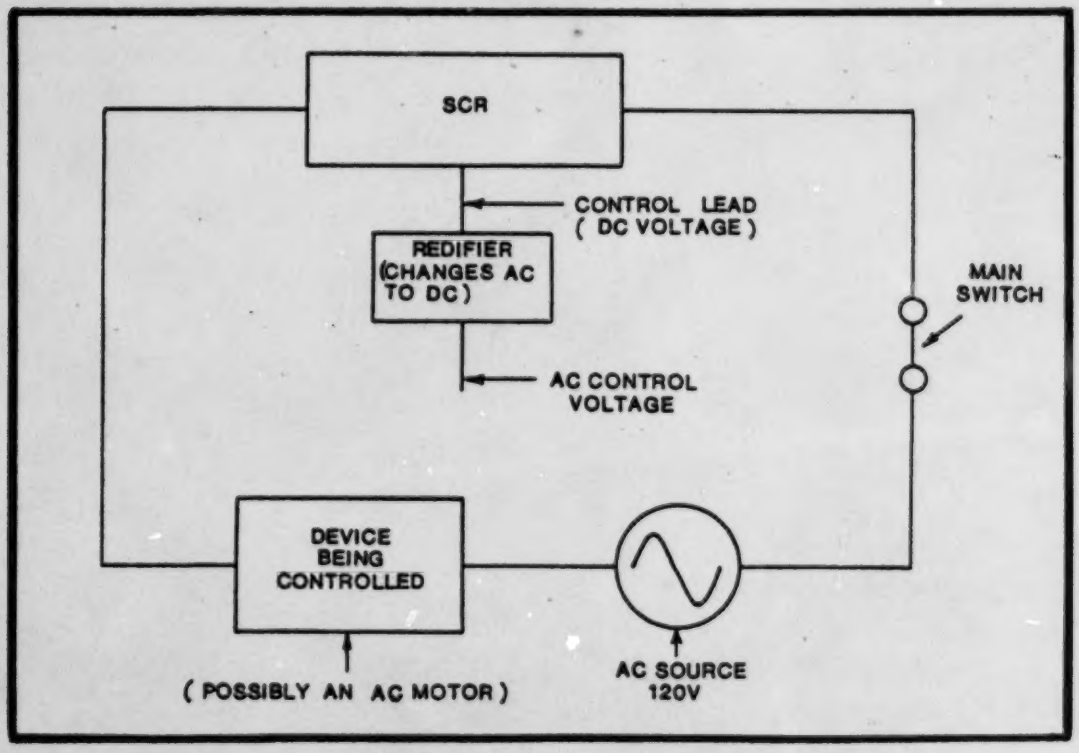


Figure 20. Block Diagram of an SCR Application.

Bidirectional Triode Thyristor

Although the SCR is useful, it has limitations when used in a.c. applications. The bidirectional triode thyristor, often called a Triac, overcomes some of these limitations.

To solve the problem of one-way SCRs, the Triac incorporates two SCRs in one case. This allows current to flow two directions through the stage. Because a.c. current is always reversing, the complete cycle can be used to provide all power instead of just half of it – as was the case with the SCR device. This is an important consideration in energy management.

For example, the Triac can control power to an a.c. motor or a light-illumination system. As long as the trigger lead is fed a voltage, the stage will turn on and allow current to flow through it. Like the SCR, a turn-off method is required for the Triac. Detailed explanations for turning off the Triac are covered in a later module.

DIGITAL TECHNIQUES

The world of electronics has lived most of its life within the concepts of analog. Analog refers to an a.c. or d.c. signal that varies continuously or smoothly; a digital signal is either ON or OFF. Therefore, a digital signal is a two-level condition. An example of a digital device is the common wall switch found in the home. When the switch is Up, it applies 120 V a.c. to lights. A Down position provides 0 V a.c. Of course, not all switches control 120 V a.c. and 0 V a.c. In the digital world, two voltages often appear: 12 volts and 5 volts.

So that the student can appreciate the difference between analog and digital, Figure 21 illustrates examples of both. Whereas analog signals are always present, digital signals are a series of ON-OFF voltages.

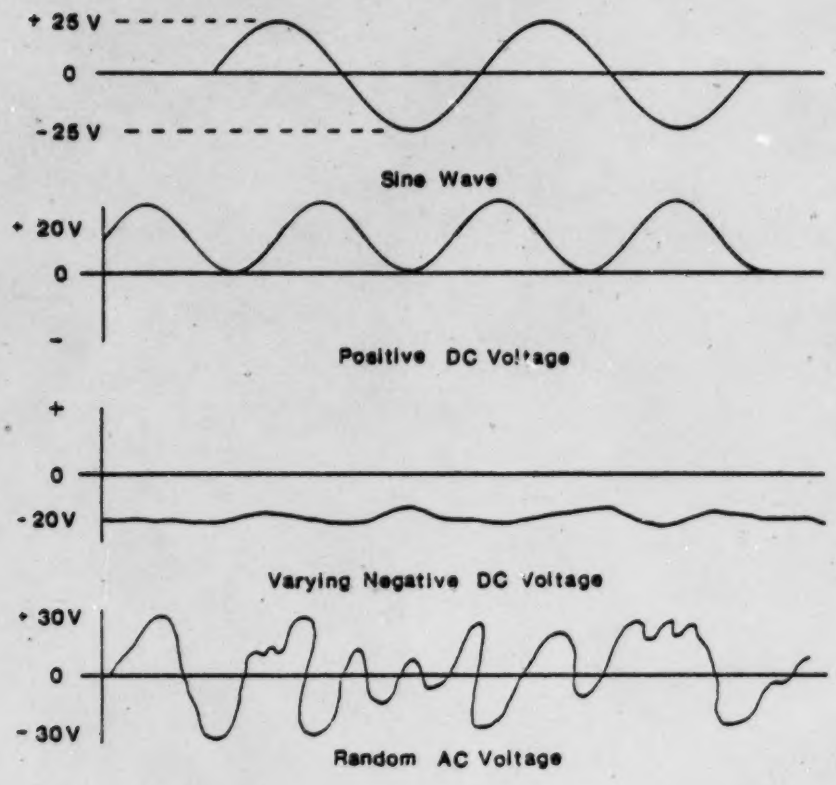
Digital signals are pulses of voltages that flip back and forth between two preset values. Figure 21b shows three examples. The top example shows ON to be +5 V d.c. and OFF to be zero; the middle example shows +12 V d.c. as ON and zero as OFF; and the bottom example shows -12 V c.c. as OFF and +12 V as ON.

These are only three examples. Many conditions can exist. Generally, it is important to remember that two states are necessary to make a signal digital.

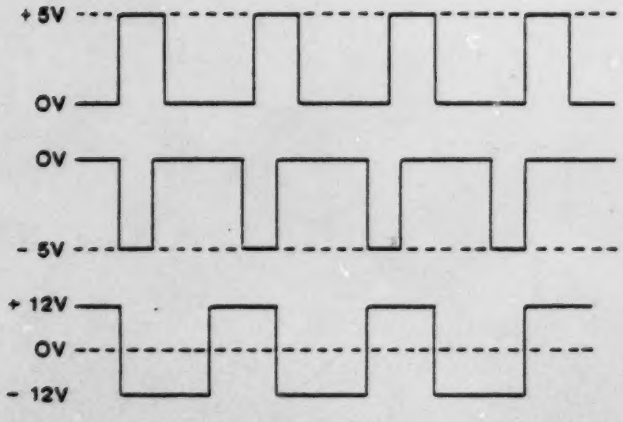
Digital devices have a major advantage over analog devices. Because of the simplicity of ON-OFF states, digital devices are much cheaper to construct. The new era of microprocessors is a classic example of this reality.

Input and output concepts and applications for digital circuits differ from analog circuits. Most digital stages modify at the output those signals appearing at the input — just as analog stages do. However, a great many digital stages and systems combine several input signals to make one output signal.

There are two basic types of digital stages: decision-making and memory.



a. Types of Analog signals



b. Types of Digital signals

Figure 21. Analog and Digital Signals.

Decision-Making Stages

Decision-making stages provide an output that depends upon a set of input conditions. However, once the output changes, this type stage cannot remember what its output was before the change. Simply stated, the decision-making digital stage has no memory. A good example of this stage type is the window and door check system shown in Figure 22.

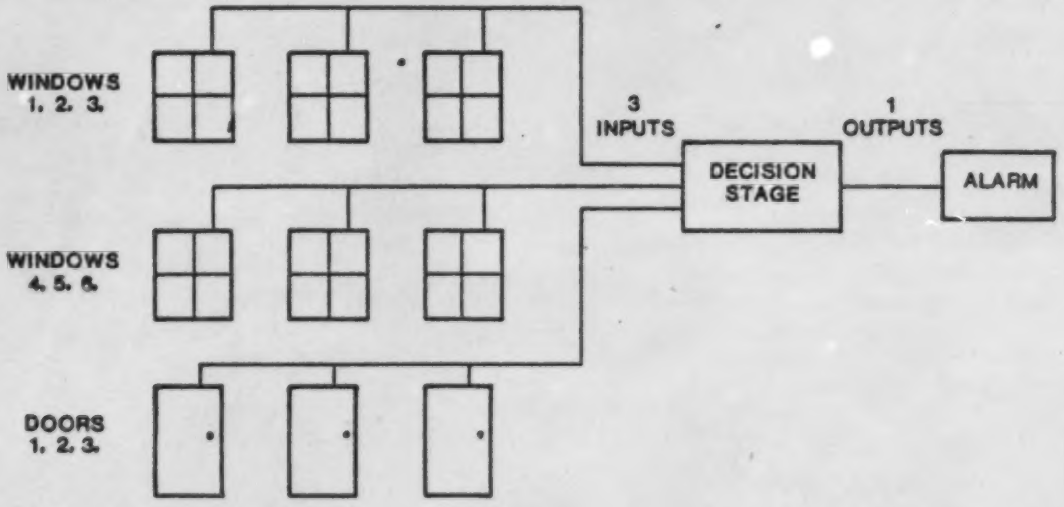


Figure 22. Decision-Making System (Window and Door Check).

In this figure, if all windows and doors are closed, the alarm remains OFF; if any are open, the alarm sounds. Although the alarm cannot determine which windows or doors are open, additional decision stages can be added to determine this information. However, once the windows and doors are closed and the alarm is silenced, the alarm not only does not remember which opening caused the alarm, it does not even know that it previously sounded.

The basic decision-making stage is called a gate. Most gates have two or more inputs, and almost always one output. Although only one gate can be used in simple stages, several are usually combined to form a larger decision-making circuit (called combinational gating or combinational logic stages). Most combinational stages provide a special logic function, such as those listed below:

- Coding.
- Decoding.
- Multiplexing.
- Comparison.
- Math operation.

This module does not discuss these functions; some are explained in later modules.

Memory

The second type of logic stage is the memory device. Each individual stage has two memory states, called flip-flop. This stage, unlike the decision-making stage, can remember two conditions: the previous condition and the present one. Because a digital signal is either ON or OFF, these two states are represented as 0 and 1. The stage is placed in either state and remains there to retain the stored condition. In this manner, the memory device "remembers."

Memory stages, when combined with decision-making stages, form sequential logic stages. Figure 23 shows a general layout of a sequential stage.

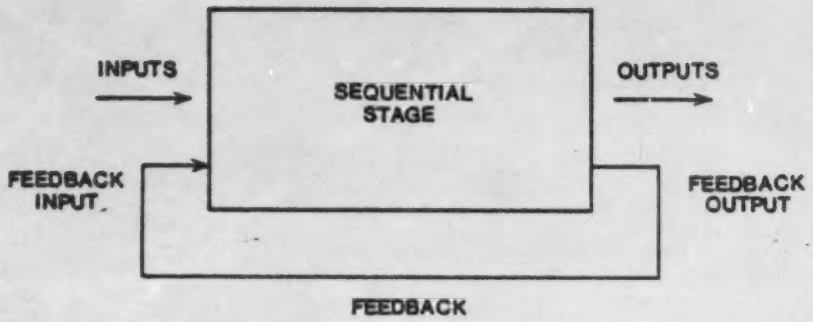


Figure 23. Layout of Sequential Stages.

Typical sequential stages are shift registers, shifters, timers, and sequencers. Each of these devices have multiple-memory stages working together to perform memory tasks.

SUMMARY

This module explained concept and application of analog and digital stages. In troubleshooting procedures, the technician must have a good understanding of the signal input and output of these stages, since stage treatment understanding is the key to determining system failure. Modules that follow include additional technical information about how the stage performs its function. Voltage and current, as well as device operation, will be covered.

1. Describe the outputs from the following stage, with the input and stage treatment as shown.

   Class A voltage amplifier.

   Input: 1.0 V a.c. (P-P).

   Stage treatment: voltage gain 12.

2. For each of the following outputs, name the specific oscillator or wave-generator stage that produces it:

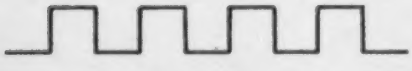
a.

SINEWAVE – 10KHZ

b.

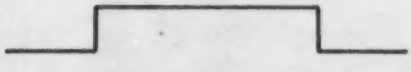
SINEWAVE – 500KHZ

c.



SQUARE WAVE – 1MHZ

d.



SQUARE WAVE – VARYING RATE

e.

SAWTOOTH WAVE – 60HZ

3. State one reason why waveshaping stages are used.
4. Name the three-stage combination that produces a d.c. voltage from a power supply.
5. State the most efficient rectifier stage discussed in this module.
6. Discuss the abilities of the following displays in terms of application:
   a. Incandescent lamps.
   b. Neon lamps.
   c. LEDs.
   d. LCDs.
7. State the disadvantage of SCRs.
8. Refer to Figure 22. Determine which window or door is open by writing a mathematical statement and describing the stages from left to right.

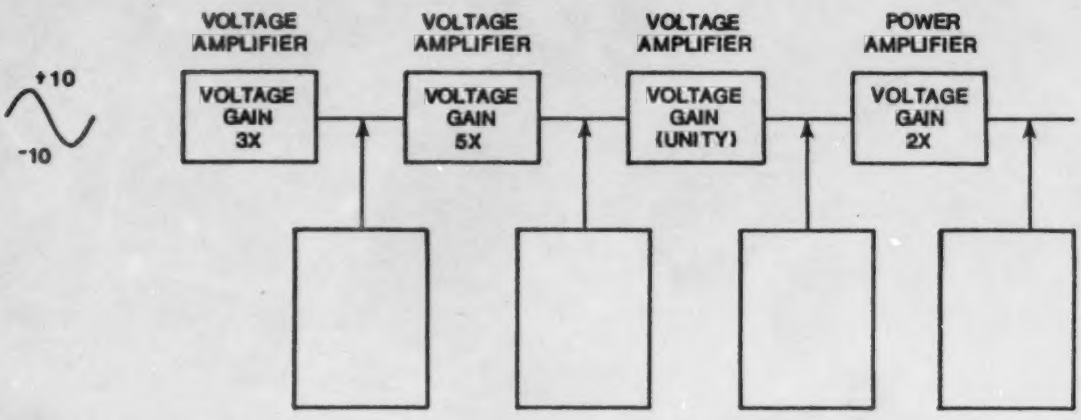
REFERENCES

Boylestad, Robert and Nashelsky, Louis. Electronic Devices and Circuit Theory. 2nd ed. Prentice Hall Publishing Company, 1978, 1972.

Evans, Charles H. Electronic Amplifiers. Delmar Publishing Co., 1979.

Floyd, Thomas L. Digital Logic Fundamentals. Charles E. Merrill Publishing Co. (A Bell and Howell Company), 1977.

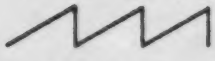
1. Using the block diagram below, draw the input and output waveshapes with P-P values that would appear at each input and output.



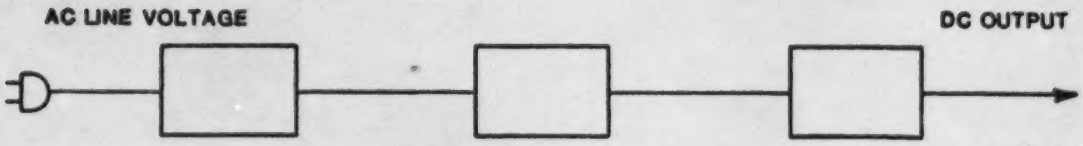
2. Where would the following ramp generator outputs be used?

a. _____

b. _____

c.  _____

3. In order, fill in the names for the following power supply.



4. State the use of the following thyristors:
   a. SCR.

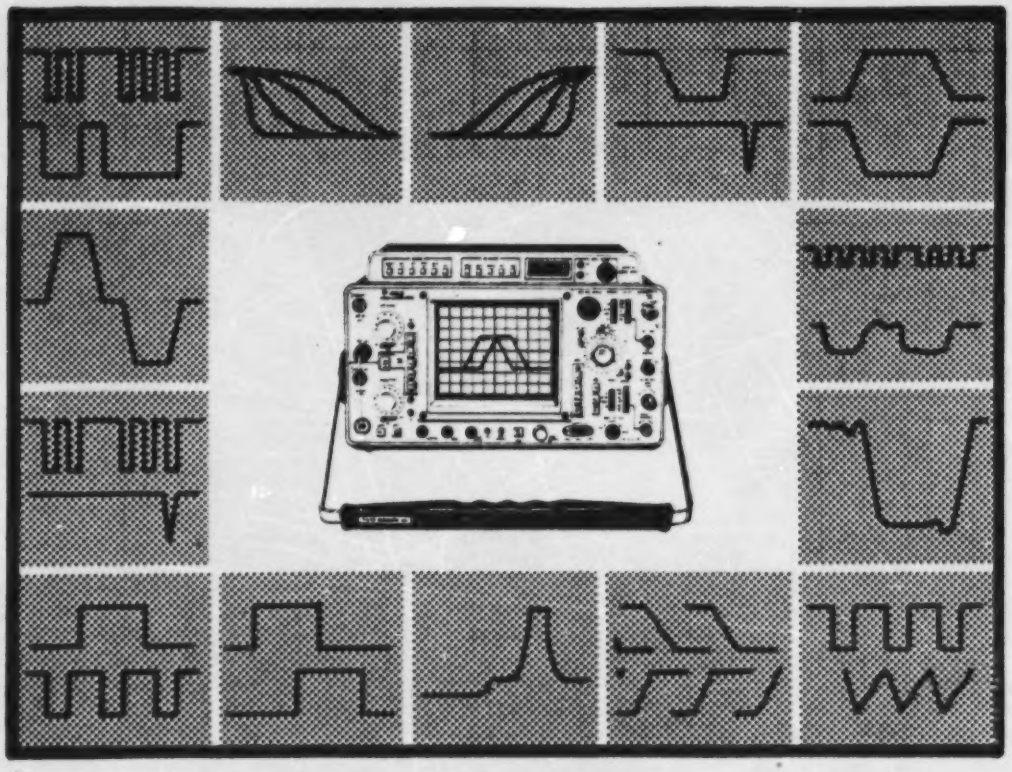
   b. Triac.

5. Name the two basic types of logic stages.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-02

VACUUM TUBES

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INTRODUCTION

Although vacuum tubes have been replaced by solid-state devices in most applications, they are still being used in high-power applications. Moreover, technicians will frequently encounter vacuum tubes in equipment that was produced in the 1960s and early 1970s. This module discusses basic vacuum tube theory and stage application, as well as tube configurations and class of operation. In the laboratory, the student will construct, operate, and test a one-stage amplifier.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe the operation of a vacuum tube amplifier.
2. Explain the purpose of bias.
3. Show how a signal flows through a tube stage.
4. Explain the three classes of tube operation and characteristics of each.
5. Describe signal appearance when a tube has distortion due to improper bias and/or to a large P-P signal.

6. Name three tube configurations and the advantages of each.
7. Name three types of couplings and the impact they have on the signal.
8. State two amplifiers used in super-high-frequency application.

VACUUM TUBE AMPLIFIERS

To understand how an amplifier functions, one must understand the device's purpose. A vacuum tube amplifier is a one-way variable resistor with gain. Its main purpose is to provide an increase in the level of the input signal at its output. While the vacuum tube amplifier can alter the shape of the signal, the term implies controlled increase. However, some stages, perhaps mistakenly called amplifiers, do not provide a stage increase – yet they provide control and treat the signal.

OPERATION

For simplicity's sake, the water system will be used to illustrate the concept of amplification. Figure 1 describes all the features necessary in an amplifier.

The control rod controls water flow by movement IN or OUT. The pump can move water regardless of the position of the control rod. If the rod is all the way into the side of the pipe, the pump simply churns the water inside the pump and moves no water through the pipe.

Notice that the rod is small compared to the pipe; this means that a small rod can control water flow in a large pipe. Herein lies the basic concept of an amplifier. Use of an amplifier in a tube enables a small change at input to effect a large change at output.

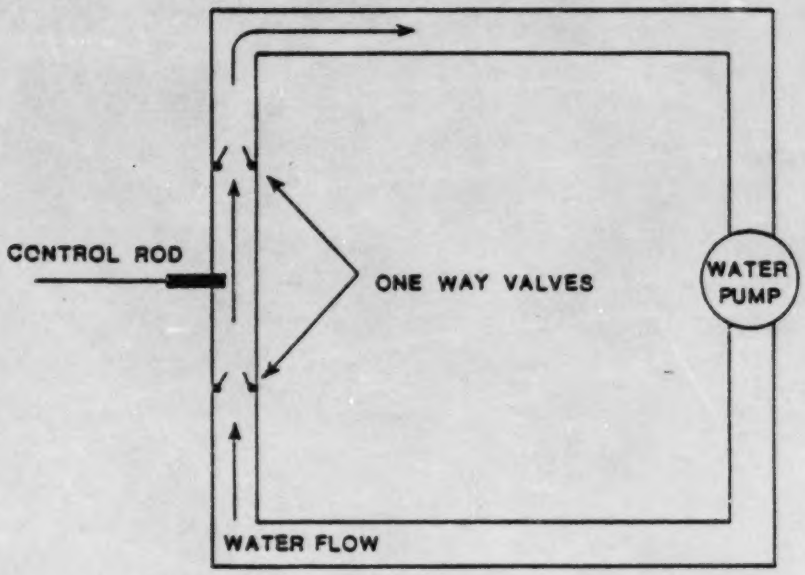


Figure 1. Water Control Rod.

In Figure 1, water can only flow through the pipe from bottom to top because of the two one-way valves on each side of the control rod. The following is a summary of the water system's features:

- Smaller input controls larger output.
- Water flows through output side in only one direction; water volume is controlled by the control rod position.

A look at the actual tube will show how these features are achieved electrically.

The tube is shown in Figure 2. Because the battery is connected with the positive lead at top (plate) and the negative lead at bottom (cathode), current can flow only from bottom to top, or from cathode to plate. To further assure that electrons (current flow) only pass from cathode to plate, a special design feature is implanted in the tube.

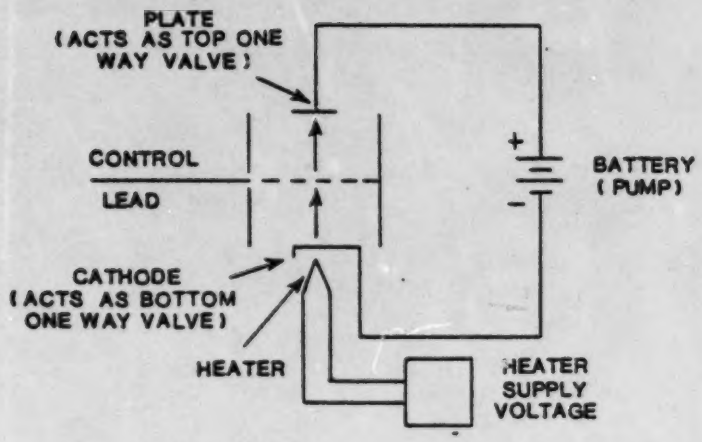


Figure 2. Tube Control.

The cathode is made from a material that has many electrons. The heater is placed close to the cathode to aid removal of excess electrons from the surface. Heating is a form of energy. Heat energy causes electrons to float above the cathode instead of resting on the cathode surface.

Because these electrons are free from the cathode surface and have a negative charge, any positive charge – if great enough – can attract them. In this application, the plate is the affecting positive charge. Assuming at this point that the control lead has no effect on the movement of electrons from cathode to plate, a preset number of electrons will migrate rapidly from cathode to plate.

The control lead is usually called a control grid. The term "grid" refers to a wire screen (mesh). Because it is a wire mesh, it has many holes. Figure 3 displays the control grid, as well as the cathode and heater.

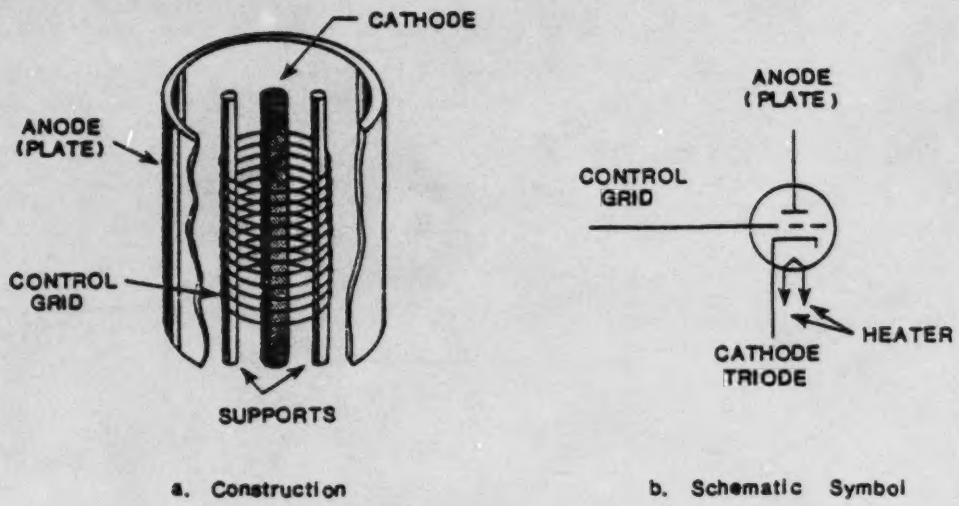


Figure 3. Tube Elements.

To make this lead control the electron flow from cathode to plate, the signal to be amplified must be applied. Assume this signal is like the one illustrated in Figure 4 below.

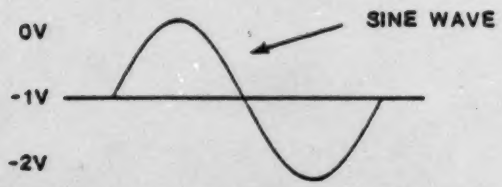


Figure 4.
Input Signal.

At this point, the student should recall some electronics basics: like charges repel and unlike charges attract.

Now, the control lead is inserted into the tube (as shown in Figure 2) with the signal applied to it. Once the control lead is placed, it will no longer move. Instead,

the voltage on the control grid determines flow of electrons from cathode to plate.

To better understand the control of this grid, refer to Figure 5 below.

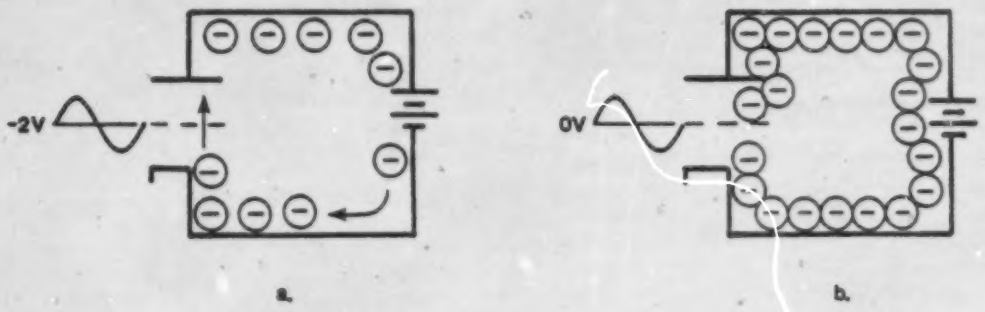


Figure 5. Output Current Flow for Input Signal Change.

In Figure 5a, note that the control grid (being -2 V) repels more electrons coming from the cathode than it does when the input signal changes the grid potential to 0 volts. Using the law of repulsion, one can see then that different amounts of grid voltage will cause current flow to change in amount from cathode to plate. If the control lead does not become more positive than the cathode, no cathode current will flow out the control lead, but will instead go out the plate.

The previous explanations show that, although the control lead will effect current flow through the tube, it will not actually use any current. In this respect, the control lead resembles the valve in the water flow system.

When no signal is present, the control lead is preset. In this state, a preset amount of current will continuously flow from cathode to plate.

There are several ways to establish this no-signal voltage; however, only one will be discussed. First, the following points must be understood:

- Control grid voltage is commonly termed "bias."
- This bias must be d.c. voltage.
- The control grid bias is always established and compared to voltage on the cathode.

CATHODE BIAS

The most common method of bias is cathode bias. In this method, a resistor is used to establish a difference in voltage. Figure 6 illustrates this method. When a current passes through a resistance, a voltage is dropped across it. With this in mind, consider placing a resistor

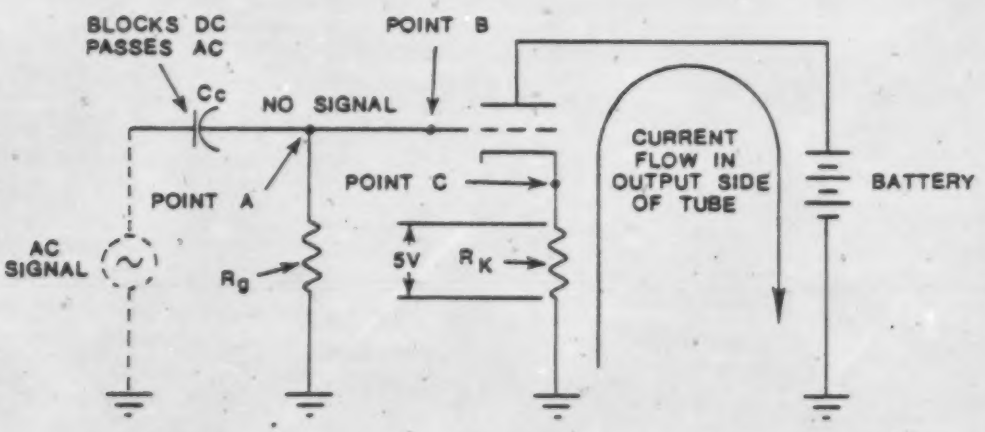


Figure 6. Static Tube Preparation.

in the cathode lead (in series) so that when a current is flowing through it, a voltage of 5 volts is dropped across it. With current flowing up through resistor R_K, the top

side is further from ground, or more positive. This makes the cathode attached to it more positive. At the same time, consider R_g in Figure 6. The electrical rules concerning resistors in parallel apply, and point A to ground is in parallel electrically with point B (through tube) to ground. As R_g is discussed, note that no signal is present. (The missing signal is the dotted line in Figure 6.)

Consider the following facts:

1. A signal (dotted line) is actually an a.c. voltage source capable of moving electrons.
2. When a signal is present, it can move electrons from ground up through R_g, through capacitor C_c, through the sine wave generator, and back to starting ground – forming a complete circuit.
3. With no signal present, no electrons flow through R_g.
4. No electrons flow from battery through R_k, through point B to point A, through R_g or through the a.c. signal source. As a result, there is no d.c. or a.c. voltage dropped across R_g. Point A then has the same potential as ground. Ground = 0 volts; point A = 0 volts.
5. Point B, therefore, is not more positive than point C.

Because d.c. current flows only through R_k, through the tube and out the plate, the only voltage drop in the circuit is across R_k. This causes point C to be more positive than point B (although point B has the same potential as ground).

Figure 6 shows that the cathode resistor R_k establishes all the voltage difference between the control grid and the cathode. No other component in the diagram can do so.

In Module ED-01, "Concepts of Input and Output," the amplifier was compared to an automobile. Using this same comparison, the following statements can be made:

Automobile
• When a car is in neutral, the engine provides the reference source for the car. • When a car is moving, and in gear, changes in the gas pedal position cause increased and decreased motion.
Amplifier
• The reference to which the a.c. signal adds to or subtracts from is the bias voltage. • A positive-going signal makes the control lead less negative and a negative-going signal makes the control lead more negative.

To make the output side of the tube conduct more current, the control grid voltage must follow changes in signal voltage by adding to or subtracting from bias voltage. To create stability in the stage, the bias voltage must remain constant, so that output changes occur only because of input signal changes.

The following summary is offered as clarification:

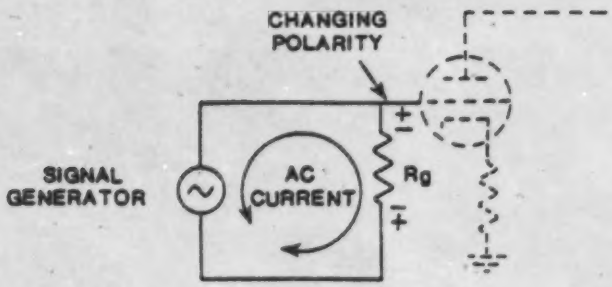
No Signal Condition

1. No a.c. or d.c. current flows through R_g; therefore, point A and ground are left at zero volts.
2. A d.c. current flowing through R_k makes point C a greater voltage than ground-zero voltage.
3. It follows, then, that the control grid is less positive than the cathode.

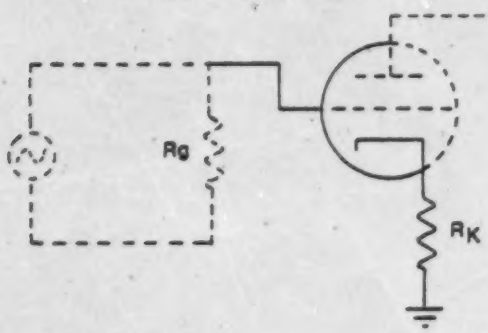
With Signal

1. A signal placed on the input causes a.c. current to flow through R_g, varying the voltage drop across it.
2. As R_g and, therefore, grid voltage change (due to signal changing), the current flow from cathode to plate changes.
3. Therefore, an input signal voltage changes the output current flow.

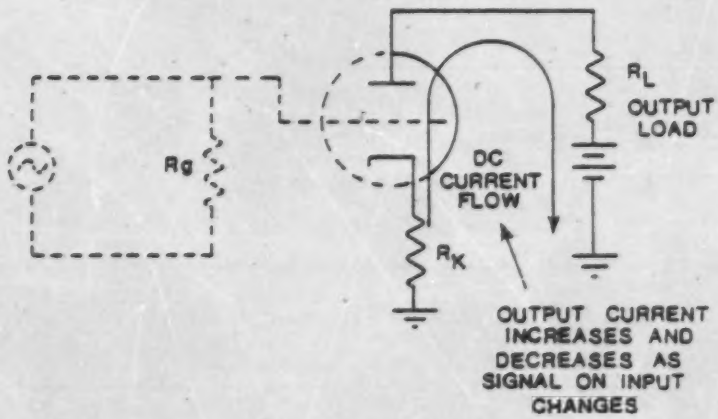
Figure 7 summarizes the condition when signal is present on the control grid. Figures 7a, 7b, and 7c correlate to Steps 1, 2, and 3 above, respectively.



a. AC Signal Generator Current Flow



b. Action by Signal on Control Grid



c. Output Current Flow

Figure 7. Signal Present on Control Grid.

To link the previous explanation with concepts of input and output discussed in Module ED-01, consider the following: the control grid is the input and the plate is the output. A stage amplification is realized, in that the small signal voltage on the grid controls the large current that flows out the plate.

CLASS OF OPERATION

Only one class of operation has been discussed thus far. If every part of the input signal is to be amplified – as was done in the previous theory – the stage has to be prepared. However, in many applications, all of the signal may not be needed. The following categories specify the amount of signal to be amplified:

- Class A – 100% of input signal reproduced.
- Class B – 50% of input signal reproduced by one tube. A second tube reproduces other 50%.
- Class C – between 20 and 40% of input signal is reproduced.

Class of operation in a tube is created by changing the d.c. bias between the control grid and cathode. In the case of Class A, a cathode resistor is usually used. Class B usually eliminates the cathode resistor; the positive alternation of the input signal causes output current to flow. However, in Class C, a capacitor and resistor attached to the input control grid usually cause the proper voltage for operation.

To gain a better appreciation of the class of operation, Figure 8 outlines the waveforms reproduced by the tube when

a continuous sine wave is placed on the control grid for three classes of operation.

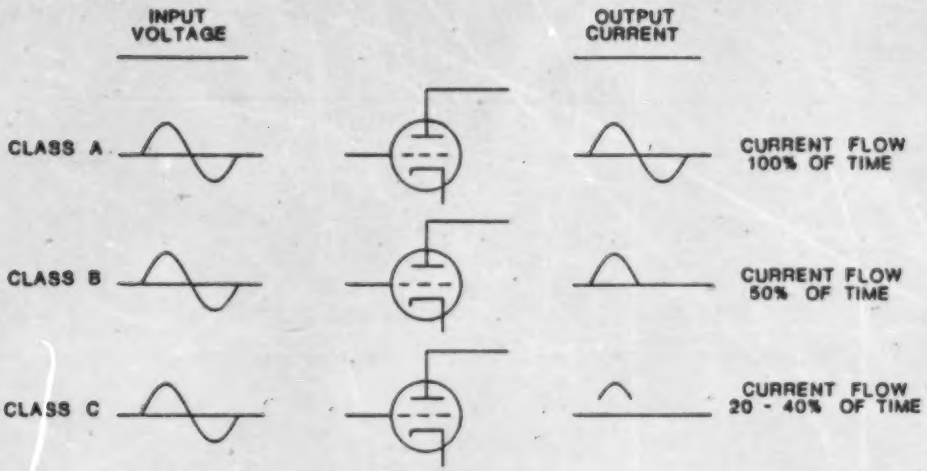


Figure 8. Input Voltage and Output Current for Classes A, B, and C.

As one progresses from Class A to Class C, less and less signal is reproduced in the output, even though all the signal is present in the input.

A stereo amplifier is an example of Class A, where the listener must hear all input sounds at output for good fidelity. If a succeeding stage in another application needs only the top of the positive peak of a sine wave to make it operate, then Class C is used. This latter example is used extensively in oscillator stages.

It is important to have proper d.c. voltages on control grids for each class of operation one wishes to create.

DISTORTION

When grid voltage (bias) is improper – or changes – during operation, some amount of distortion occurs as a result. The intended output will be altered because of the input voltage error. Two examples of distortion are shown in Figure 9.

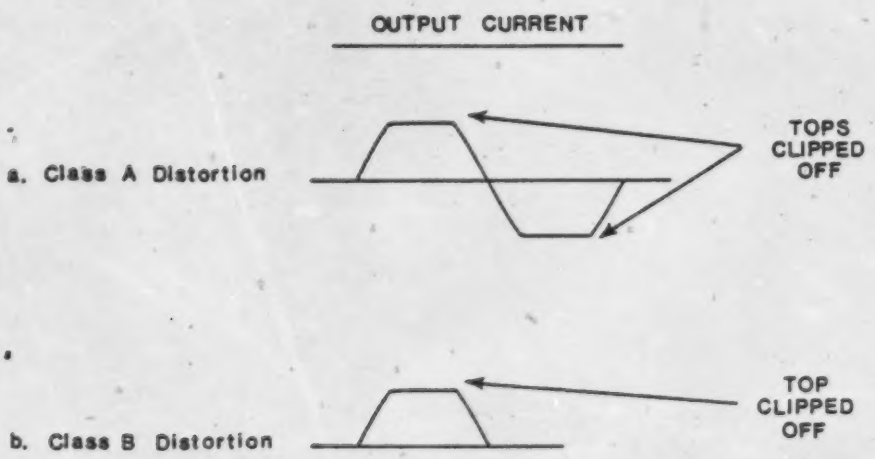


Figure 9. Distortion of Class A and Class B.

In Figure 9a, the audio from a speaker would sound slightly distorted or garbled because the top and bottom of each cycle is missing; thus, a part of the wave is not heard.

The proper bias on a tube may be checked by using a d.c. voltmeter, by placing the positive lead on the control grid and the negative lead on the cathode. The voltage read will be the difference in potential between these two parts of the input section. One must then check technical data to determine proper voltage values.

Thus far, tube operation, class of operation, and distortion have been discussed. Tubes are further categorized as to their function in a given stage or system. As stated in Module ED-01, two general categories are voltage and power. Note the following functions of Classes A, B, and C:

1. Class A amplifiers are usually voltage amplifiers (with some exceptions).
2. Class B are usually power amplifiers.
3. Class C are used for voltage and power stages as follows:
   a. Radio frequency power amplifier stages.
   b. Oscillator/amplifier stages.

AMPLIFIER CONFIGURATIONS

To satisfy specific requirements in a system, various amplifiers can be classified according to circuit configuration. A configuration is defined as "an electrical hookup showing the input and output and method of achieving operating voltages."

The following three configurations are created in tube stages:

- Common cathode.
- Common grid.
- Common plate.

Each configuration achieves specific goals. These goals are charted in Table 1.

TABLE 1. COMPARISONS OF CONFIGURATIONS.					
	Amplification				
				Input/Output Resistance	
Configuration	Voltage	Current	Power (EXI)	Input	Output
Common Cathode	High	High	Highest	High	High
Common Grid	Highest	None	Good	Lowest	Highest
Common Plate	None	Highest	Good	Highest	Lowest

Although Class A, B, or C operation is not specified, the three configurations' classes of operation would be chosen according to engineering requirements. Any one of the three classes could be used in any one of the three configurations, depending upon application. The following paragraphs contain in-depth discussions of these configurations.

Common Cathode

The prevalent configuration is the common cathode. The basic operation of a vacuum tube (discussed at the beginning of this module) is accomplished by using a common cathode stage. Figure 10 illustrates the electrical diagram showing input and output signals.

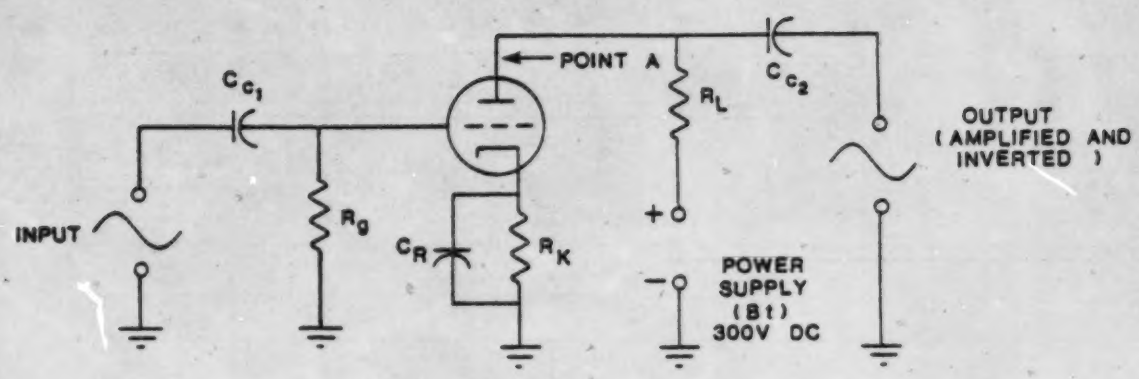


Figure 10. Common Cathode Amplifier.

The input signal is applied between the control grid and ground. Notice that the first alternation of the input signal is positive-going. This signal on the input controls the current flow from ground through R_k, through the tube and down through R_L. Because R_L is a resistor, it has a changing voltage drop.

If this changing E_{RL} is subtracted from the 300 V d.c. power supply, it will cause the voltage from point A to ground to change. This voltage change from point A to ground is the voltage signal that is sent on through capacitor C_{C_2} to the next stage. Capacitors C_{C_1} and C_{C_2} are necessary to keep out any d.c. voltages that are being fed to any previous or succeeding stages.

Capacitor C_k, called an a.c. bypass capacitor, is necessary to create good stability and gain in the stage. Note that in the output, the voltage signal is inverted from the input voltage signal. The common cathode stage turns the signal upside down – or more commonly, shifts the signal 180°.

The common cathode configuration (Table 1) provides good voltage and current increases from input to output. Although this configuration can be used to increase power, it is used most often as a voltage amplifier.

This stage and other types can be checked for proper operation by using a voltmeter and oscilloscope. The voltmeter is used to check the d.c. bias voltage and d.c. plate voltage. The oscilloscope is used to look at the input and output waveform. In the lab exercises at the end of this module, the student will have an opportunity to use both the voltmeter and the oscilloscope.

Common Grid

The common grid configuration is used where a low input resistance and a moderately high output resistance exist. A low input resistance indicates that a reasonable input current can flow. A high output resistance indicates that little current can flow in the output.

The common grid stage is used when the previous stage has a low output resistance from its plate circuit, and the succeeding stage has a moderately high input resistance in its grid circuit.

Because the input signal is fed to the cathode and the control grid is grounded, the input and output are electrically isolated. However, the stage still acts as an amplifier.

In the study of cathode bias, it was stated that "a small signal change on the control grid causes a large signal change in the output." In the common grid stage, the

change in the input circuit is made on the cathode, and the grid is stationary. As long as the signal controls input, it will also control output. Figure 11 shows the common grid stage.

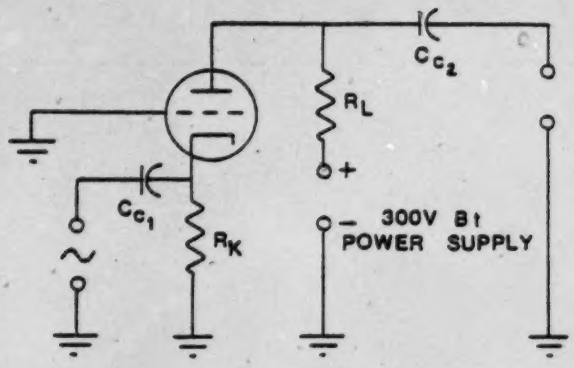


Figure 11. Common Grid Amplifier.

The output side of the common grid stage functions exactly like the output side of the common cathode stage. However, there is <u>not</u> a 180° phase shift from input to output.

Although the common grid stage has no current gain, it does have the highest voltage gain of all three configurations. The power gain is only medium.

The common grid stage is used in very high frequency applications because the grounded grid causes the input to be isolated electrically from the output.

Common Plate

The common plate stage is used for impedance matching. When a previous stage has a high output resistance and the succeeding stage a low input resistance, the common plate stage matches the two. Figure 12 shows the common plate stage.

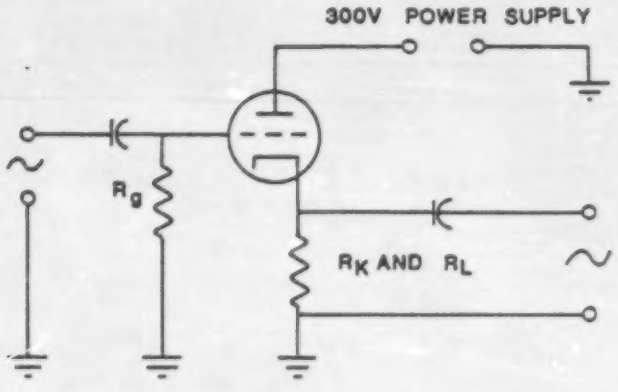


Figure 12. Common Plate Amplifier.

The input signal is placed on the control grid, with output taken across the resistor in the cathode lead. The input resistance is high, and little signal current flows. However, the output resistance is approximately equal to $R_k - R_L$. The value of this resistor is very low compared to input resistance.

This configuration is often called a cathode follower stage. Output signal tends to follow input signal; that is, the signal is not phase-inverted. Although the cathode follower stage has no voltage gain, it does have high current gain and reasonable power gain.

In summary, it must be noted that specific application dictates which configuration is used. In any system, the common cathode stage is most prevalent, followed by the common plate stage. The common grid configuration is not as frequently encountered; however, it is used in high frequency communications equipment.

STAGE COUPLING

The signal must be transferred from one stage to the next. This is accomplished by capacitive coupling, transformer coupling, or direct current coupling. Examples of each will be discussed in the following paragraphs.

Capacitive Coupling

From the study of capacitors, it can be recalled that this device passes a.c. current flow and blocks d.c. current flow. When used as a coupling capacitor, its capacitance value is chosen to present the lowest possible capacitive reactance to the a.c. current that is flowing. Because different signal frequencies flow in a given system, each application has to be calculated individually. Figure 13 shows two examples with different frequencies applied.

Capacitive coupling is the most common type of coupling used in audio stages. However, d.c. coupling is also used, since capacitors always provide a voltage loss when used as coupling devices, and d.c. coupling eliminates these capacitors.

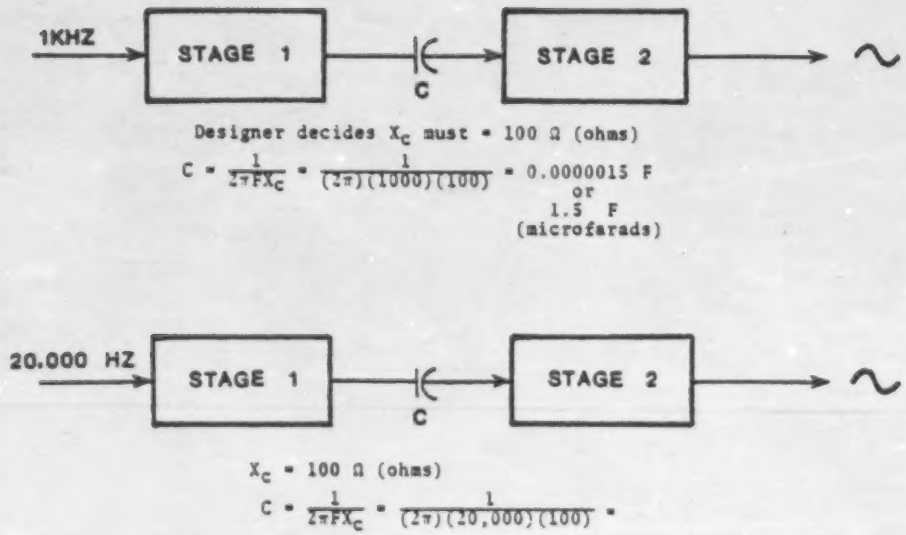


Figure 13. Capacitive Coupling.

Figure 14 illustrates a three-stage capacitive coupled amplifier. Three Class A stages with capacitive coupling are shown in the figure. The frequency range of the input here could be around 50 Hz to 15,000 Hz, or in the audio frequency range. The coupling capacitors, C_1, C_3 and C_5, couple this signal from the turntable and from stage to stage. Each amplifier operates Class A and is a common cathode configuration which provides both voltage and current gain. Because the last stage drives a speaker, it is more a current amplifier than the previous stages were.

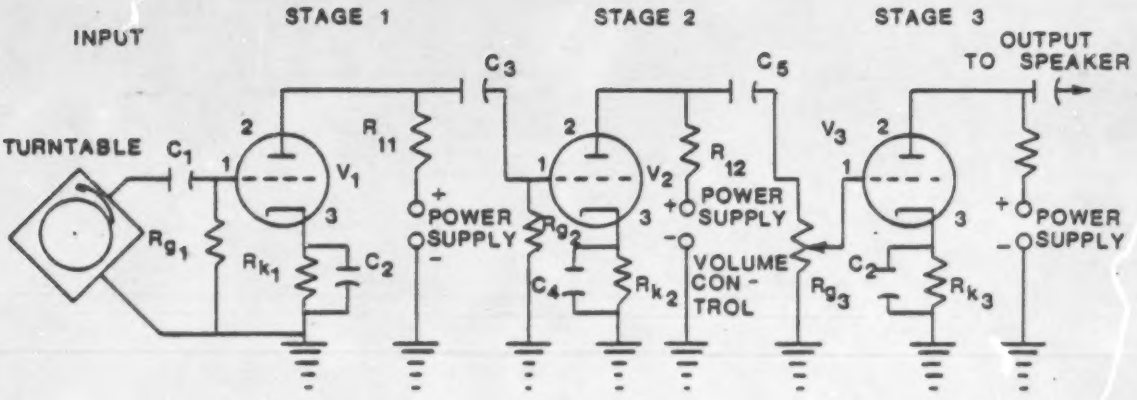


Figure 14. Three-Stage Capacitive Coupled Amplifier.

Transformer Coupling

A transformer reacts to a changing a.c. signal. Similar to capacitors, these devices pass a.c. and block d.c. Remember, transformers are impedance-matching devices and, therefore, can be used between stages to pass a.c. signals while keeping d.c. voltages in their respective areas. Figure 15 shows two examples of transformer coupling.

Figure 15a shows that resistance in the output of stage 1 is equal to the resistance of the input of stage 2. For example, if the voltage level in the primary is 10 volts a.c., then the voltage in the secondary is approximately 10 volts (excluding any loss in the transformer). The transformer in Figure 15b shows a voltage step down because of the resistance ratio of 100:1 (10,000Ω/100Ω). In this application, the voltage in the secondary is considerably less than the voltage in primary. According to transformer theory, a voltage reduction produces current increase, as shown by the following ratio:

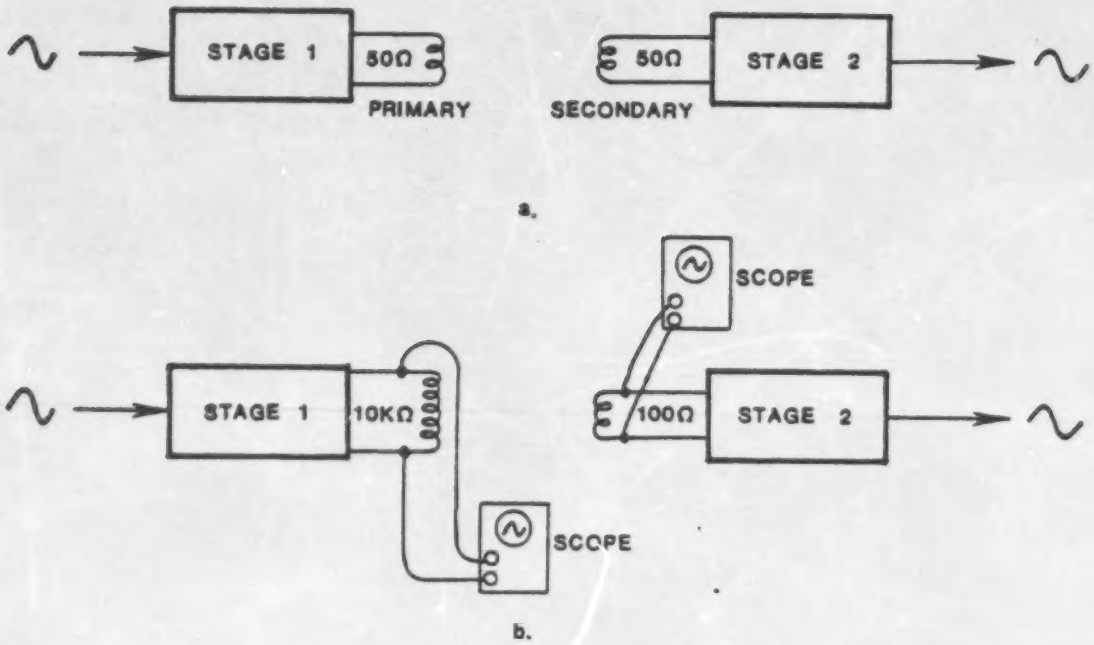


Figure 15. Transformer Coupling.

$\frac{Ep}{Es} = \frac{Is}{Ip}$ voltage to current ratio

This formula states that the current ratio is a reciprocal of the voltage ratio. In Figure 15b, when looking at the signal in the primary and secondary with an oscilloscope (an oscilloscope records voltage), the secondary will have a much smaller P-P voltage value.

Assume that the same range of frequencies was inputted to the three-stage transformer coupled system in Figure 16 as was inputted to the capacitive coupled system. Transformer coupling, as compared to capacitive coupling, limits the low and high frequencies of the signal because of the properties of the transformers. Instead of 50 Hz, the low

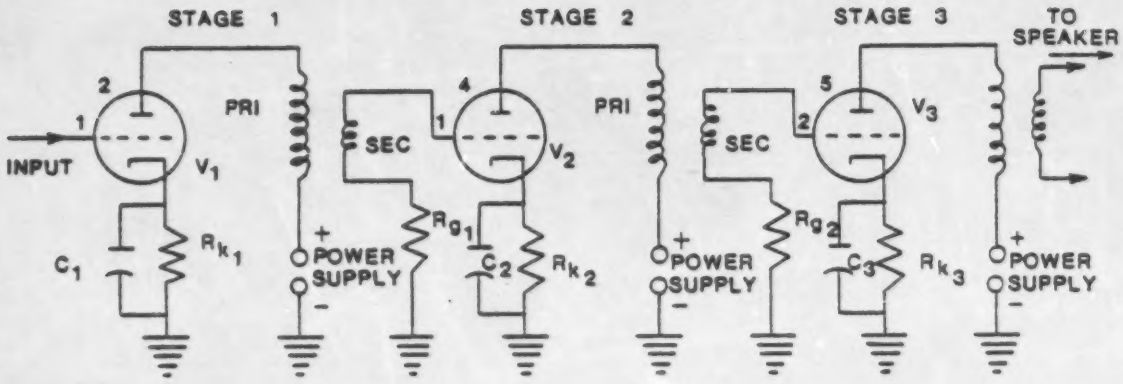


Figure 16. Transformer Coupling.

end may be 105 Hz, thereby limiting low, or bass, frequencies. Moreover, the high frequency may end at 12,000 Hz, instead of 15,000 Hz, thereby reducing treble frequencies.

Recall from previous data that the transformer passes the a.c. signal and keeps the respective d.c. voltages in the stages that the d.c. voltages are operating.

Direct Current Coupling

In the two previous types of coupling, d.c. voltages are blocked, passing only a.c. signal voltages. When direct current (d.c.) coupling is used, both d.c. and a.c. voltages are passed from one stage to the next. Figure 17 illustrates this type of coupling.

Figure 17a shows output from stage 1 connected wire to the input of stage 2. Figure 17b shows a resistor between the two stages. Because a resistor passes d.c. and a.c. voltages – as does a wire – the two stages share both d.c. and a.c. voltages. Although the resistor does reduce d.c. and a.c. voltages, it allows both to pass.

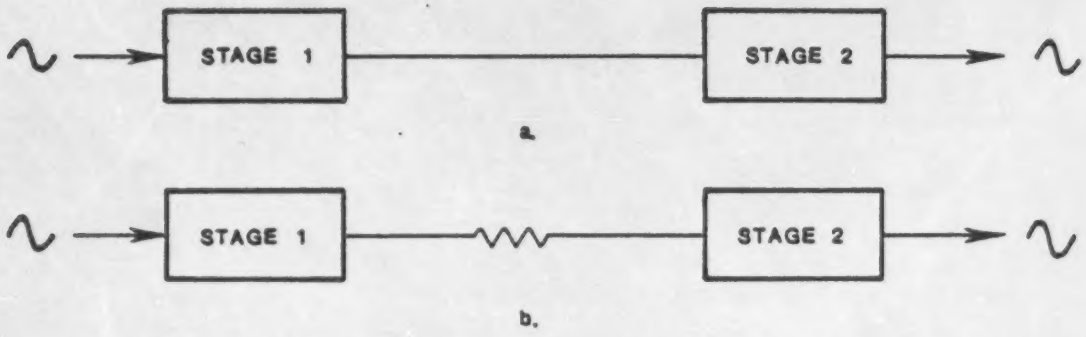


Figure 17. Direct coupling.

In tube circuits, d.c. coupling is not commonly used. However, when solid-state devices are covered in later modules, this type of coupling will be discussed.

MISCELLANEOUS TUBE CIRCUITS

Specialized circuits are often employed in electronics. Some frequently-encountered specialized circuits will be discussed in the following paragraphs.

Laser Amplifiers

Recent developments in electronics have produced the laser. The term "laser" is the abbreviation for light amplification by stimulated emission of radiation. Although the eye cannot see the beam of light the laser produces (its frequency is beyond the range of human vision), the laser can be used to transmit information. Communications is making

considerable inroads; however, the medical field has made the most significant contributions to the development of new applications for lasers.

Traveling-Wave Tube Amplifier

A similar device to the laser is the traveling-wave tube (TWT). The basic form of this device contains an electron gun which beams a stream of electrons through a helically-wound coil to a collector electrode. A signal is inputted to the input side and interacts with beam and helical coils to create a modulated wave at a super high frequency (SHF). This unit, a low voltage output device, is often used to provide input to a final amplifier, such as a klystron. Figure 18 shows the basic TWT.

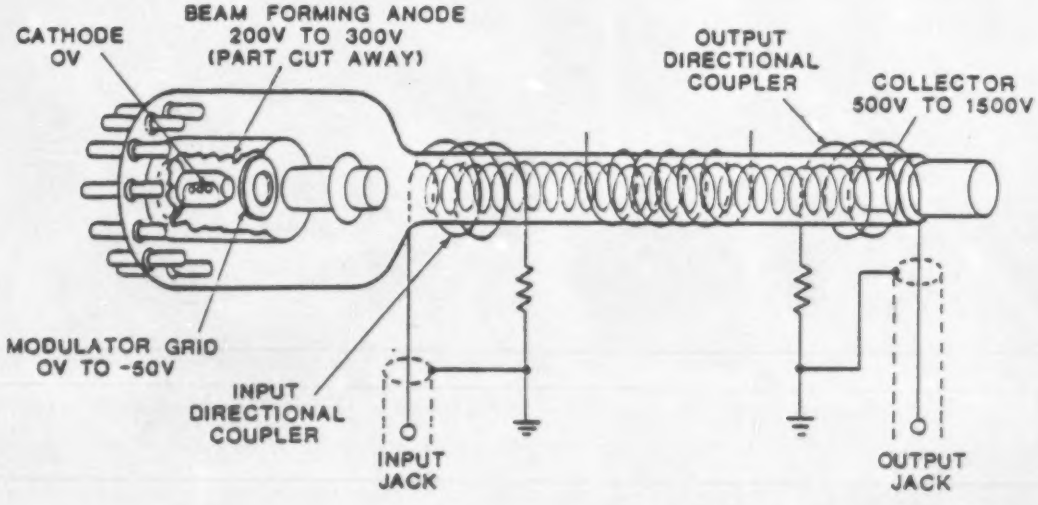


Figure 18. The Traveling-Wave Tube Amplifier.

Klystron Amplifier

A klystron device can also be used to amplify signals in the microwave frequency range. Similar to the TWT, an electron beam in the klystron device is fed from a cathode toward the collector. A signal placed on the input terminal causes electrons coming from the cathode to change speed, creating bunching and expansion along the length of the tube. Figure 19 shows this condition. The end result is a modulated wave at the output.

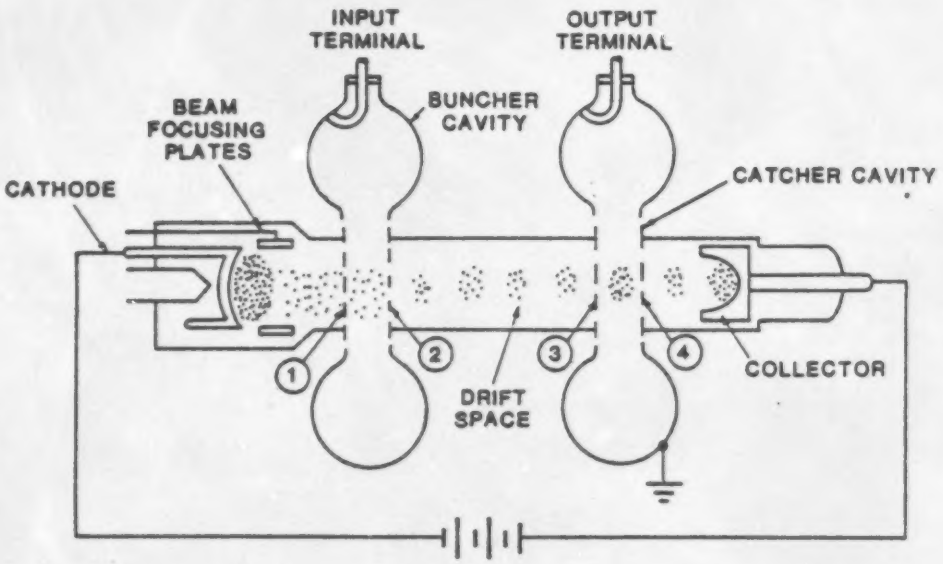


Figure 19. Two-Cavity Klystron Amplifier.

This device is usually used to drive an antenna which is used in a communications network (like those atop telephone offices).

SUMMARY

Several points concerning vacuum tubes and their applications are summarized below:

- Tubes are sealed in a vacuum.
- Most tubes provide amplification to the signal placed on the input.
- Stage resistances must be matched so the signal will be transferred successfully without heavy losses from one stage to the next.
- Depending upon the needs, tubes can be configured and classed to provide specific characteristics necessary for desired signal treatment.
- Basic theories of tubes can be altered to provide a variety of tube applications.

Although only the one-grid tube was used to explain vacuum tube operation, multi-grid tubes are also in use. When a tube has additional grids constructed within the tube, grids usually have been added to improve tube operation as a transfer and amplifying device. Consequently, multi-grid tubes have sometimes been added to modern tube equipment.

EXERCISES

1. Research, then draw diagram symbols for the following tubes:
   a. Triode.
   b. Tetrode.
   c. Pentode.
2. Draw three configurations and show how input signals and output loads would be connected. (Use capacitor coupling on the input sides of the stages and transformer coupling on the output sides.)
3. Research, then state the general classification of the range of frequencies from audio to ultra-high radio frequencies.

LABORATORY MATERIALS

Equipment:

1 power supply, 0-300 V d.c., 5-10 mA ability (regulated).
1 power supply, 0-10 volts, 1-5 mA ability (regulated).
2 vacuum tube voltmeters:
    d.c. volt range: 0-1000 V d.c.
    a.c. volt range: 1-20 V a.c.
1 oscilloscope, triggered 5 mHz dual trace.
or
2 oscilloscopes, triggered 5 mHz single trace.
1 0-20,000 Hz signal generator (audio).

Components:

2 8-12 microfarads, 600 WV d.c.
2 resistor sub-boxes, Heathkit EU-28A or equivalent.

1 120 V a.c./12-6 V a.c. filament transformer.
1 12 AX 7.
1 breadboard to accommodate tube hookup.
1 1KΩ 2 watt 5% resistor (carbon).
1 100KΩ 2 watt 5% resistor (carbon).

LABORATORY PROCEDURES

VACUUM TUBE AMPLIFIER

In this experiment, the students build and operate a triode amplifier.

PROCEDURE

1. Look up the tube base diagram in a tube characteristic manual to determine socket pin connections. Use the left side of the tube diagram for hookup.
2. Connect 1/2 or 12AX7, as shown in Figure 20.

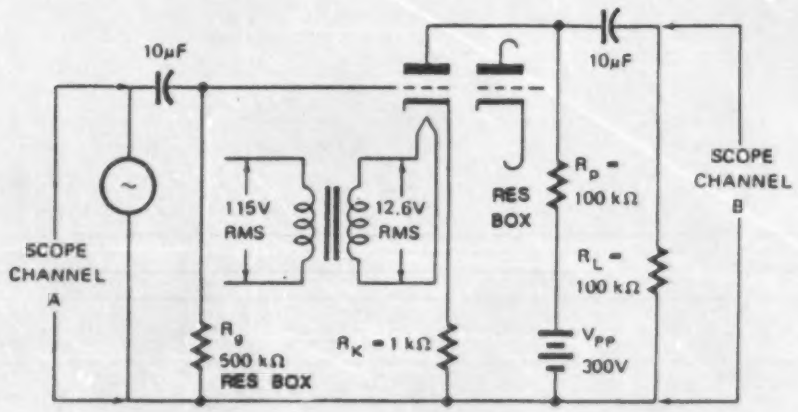


Figure 20. Schematic for Triode Amplifier.

3. The V_{pp} power supply should be connected with the (+) terminal toward the plate.
4. Prewarm the oscilloscope and signal generator.
5. After the instructor has checked the circuit for correct connections, turn on the filament power supply and wait about 1 minute. Then turn on the 0-300 V d.c. power supply. (No waiting is necessary for the 0-300 V d.c. power supply.)
6. Adjust the signal generator so there is approximately a 0.5 V a.c. signal (P-P) showing on scope channel A. Place this value in the Data Table.
7. Measure the output on scope channel B. Record results in the Data Table.
8. Using A out/A in, calculate the voltage gain. Place the result here: _____.
9. Adjust the resistance boxes used for R_g and R_p so that the greatest amplitude with the least distortion is obtained. Record these values below:

   R_g _____ R_p _____

10. Does this tube invert the signal from input to output?

    _____

DATA TABLE

DATA TABLE. VACUUM TUBE AMPLIFIER.

INPUT	OUTPUT
Input voltage _____	Output voltage _____
Wave shape:	Wave shape:
_____	_____

REFERENCES

Evans, Charles H. Electronic Amplifiers. Albany, NY: Delmar Publishing Co., 1979.

Educational Services, Inc. This is Electronics: Circuits and Applications. Indianapolis, IN: Howard W. Sams and Co., Inc., 1970.

1. The control grid in a Class A stage conducts current flow.
   a. True _____.
   b. False _____.
2. When the control grid in a Class A stage becomes more negative, the plate current increases.
   a. True _____.
   b. False _____.
3. As far as the power supply is concerned, list the classes of operation in order of their efficiencies.
   a. _____.
   b. _____.
   c. _____.
4. As far as the signal reproduction is concerned list the classes of operation in order of their distortion.
   a. Least _____.
   b. _____.
   c. Most _____.
5. As far as frequency response is concerned, list the three types of coupling in the order they limit the range of the input signal.
   a. Most limiting _____.
   b. _____.
   c. Least limiting _____.
6. What type of configuration is used for a high frequency amplifier when input to output isolation is required?

   _____
7. Which configuration has the following:
   a. Most power gain _____.
   b. Most voltage gain _____.
   c. Most current gain _____.

8. Bias in a tube is used to do the following:

   a. Set the static conditions of a tube _____.

   b. Set the dynamic conditions of a tube _____.

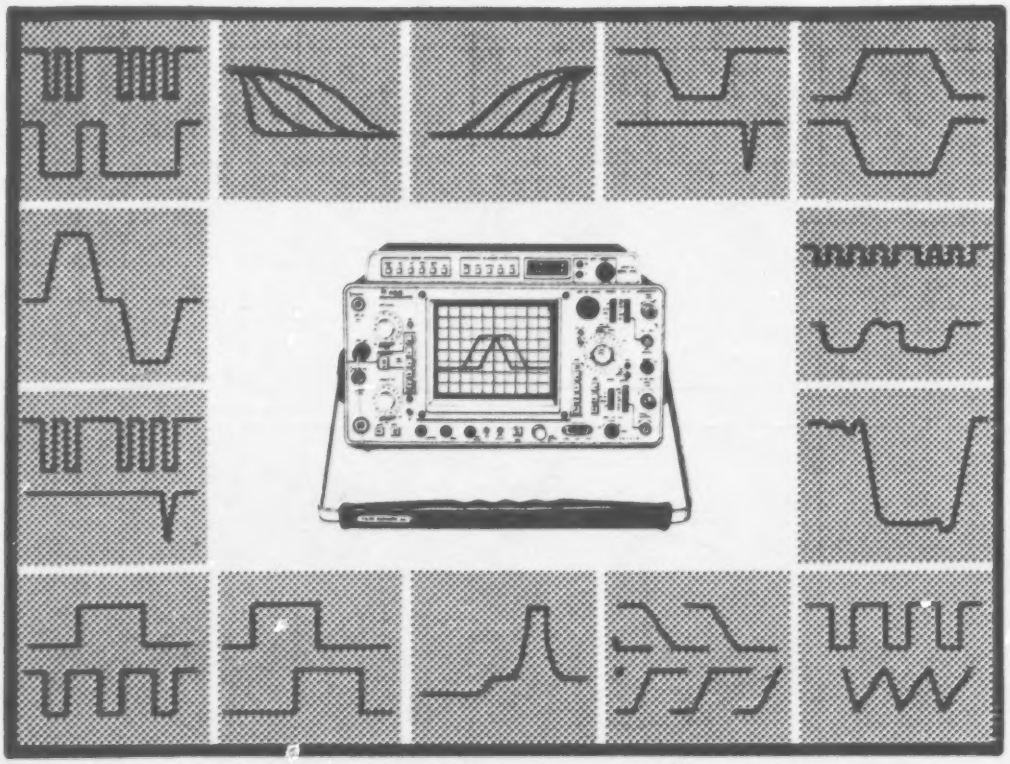
   c. Modulate the tube _____.

   d. None of the above _____.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-03

SOLID STATE DEVICES

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4800 LAKEWOOD DRIVE, SUITE 5
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INTRODUCTION

SOLID STATE DEVICES

Semiconductor diodes and transistors are classed as solid-state devices because the electronic action occurs in a solid crystal, semiconductor material. Because these devices are small and lightweight, have no filament, and are economical to manufacture, they are rapidly replacing almost every vacuum tube application known – except the high-power tubes used in some transmitters. This module discusses basic physics and electrical properties of solid-state devices, as well as practical applications. In the laboratory, the student learns the operation of a common emitter amplifier and testing procedures for bipolar transistors.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Name advantages of bipolar transistors over tubes.
2. Name disadvantages of bipolar transistors.

3. State atom structures of 3-, 4-, and 5-valence-ring electrons and combinations thereof to form N- and P-materials.
4. Describe the process of using both one and two junctions to form P-N diodes and P-N bipolar transistors. Include both NPN and PNP transistors.
5. Explain atom structure differences between NPN and PNP transistors.
6. With an ohmmeter, successfully test an NPN and PNP transistor for junction condition.
7. Explain differences between bipolar and unipolar transistors.
8. Define the terms "depletion mode" and "enhancement mode" as they relate to an IGFET.
9. State a reason why gates can never be made positive for a N-channel JFET or depletion mode N-channel IGFET, and state a reason why gates can never be made negative for a P-channel JFET or depletion mode P-channel IGFET.
10. State safety precautions to be taken in the use of IGFETs.

Discrete, solid-state devices are divided into two primary categories: bipolar and unipolar. Bipolar devices are constructed with semiconductor junctions; whereas, unipolar devices consist of one semiconductor material. This module discusses bipolar devices, as well as the more advanced unipolar field-effect devices.

BIPOLAR DEVICES

Considering the advantages of solid – state devices, it is understandable that the electronics industry has capitalized on their use whenever possible. Following is a list of the advantages they pose over vacuum tube devices:

- No filament.
- Longer life expectancy.
- Compact.
- Lightweight.
- Less fragile.
- Instant-ON.
- Lower power-supply voltages.
- Less operating current requirement.

In constructing any system, both size and weight play an important role. Energy use, in particular, is a critical consideration in design. Moreover, the space race has demanded rugged equipment that can withstand vibration and changing temperatures yet can respond at the flip of a switch. All of these requirements are satisfied by the introduction of the semiconductor.

However, solid state devices do have certain flaws. Below is an example of some of the disadvantages attributed to solid state devices:

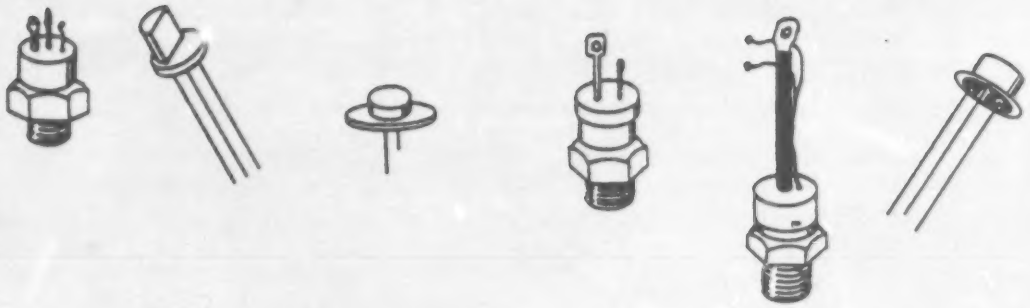
- Sensitive to heat during operation or storage.
- Sensitive to signal over-driving.
- Sensitive to excessive operating voltages.
- High internal noise.

If too much current passes through a solid-state device, it becomes overheated and is damaged. This condition can be caused by any one of the first three disadvantages discussed above. Whether it be external ambient heat, or internal heat caused by signal and/or voltage, the device can be destroyed rapidly.

To prevent such damage, many of the devices shown in Figure 1 must have metal heat dissipation units placed on them as an attachment. Without these add-ons, the solid-state device has to be operated at a lower output rating to assure a lower heating level.

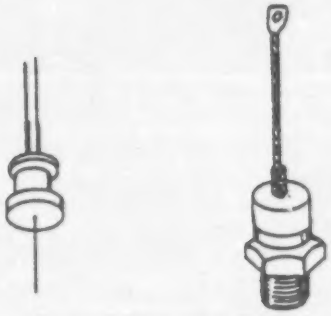
The fourth disadvantage stated is noise. Because of construction and the nature of the materials, these devices internally exhibit random movement of electrons while they are operating. This leads to noise being added to the signal as it passes through the device. If heat level of the device is kept low, noise level is reduced.

Figure 1 shows a variety of solid-state devices. Figure 1a displays power transistors at the top and voltage transistors at the bottom. These devices usually require a heat sink because their operating temperature is higher than the smaller, lower-power units which are shown at the bottom of Figure 1a.

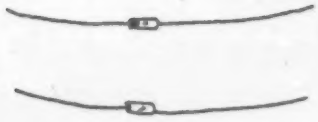


a. Translators

b. Silicon Controlled Rectifiers (SCR)



c. Rectifier Diodes



d. Signal Diodes

Figure 1. Solid-State Devices.

Figure 1b shows electronic switches used to turn ON and OFF d.c. and a.c. current flow. These devices are often used to control both low and high currents in electronic and motor control circuits.

Figure 1c shows power supply diodes which are used specifically for rectification. The size of these devices tells something about the amount of current that can be passed through them without damage.

Figure 1d displays diodes used to rectify in the signal path. These devices have special characteristics so they can operate properly at a given frequency. They are often used to demodulate a signal. Demodulation is a process used in communication equipment where the signal from a transmitting station is treated by receiver stages so the signal produced originally can be received.

SEMICONDUCTOR MATERIALS

Semiconductor devices and packages are constructed in a variety of ways and from different materials. Two of the materials used are germanium and silicon. Germanium was used to make semiconductors in the 1940s and 1950s. Silicon has replaced germanium in recent years.

The term "semiconductor" originates from the awareness that the device is "in between" an insulator and a conductor as far as its resistance is concerned. Free electrons determine what characteristics a material will have, and whether that material is a conductor or an insulator is determined by its molecular structure. Because a combination of materials from both insulator and conductor classes are used to form a semiconductor, there must be a method to combine the different atoms of each material.

Figure 2 shows an insulator atom which has four electrons in its valence ring. (A valence ring is the outermost ring in any atom.) An atom with this condition indicates a stable unit in which the atoms are bonded (by the nucleus) to the hole in which they reside. Because the atom is stable, it is difficult to break these atoms free. In other words, there are no free electrons which an electrical potential can move easily.

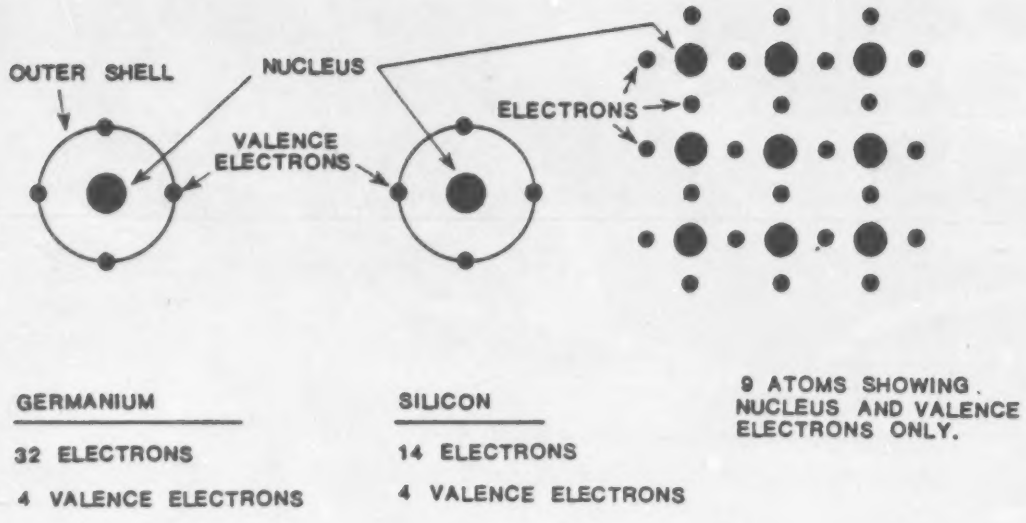


Figure 2. Insulator Silicon Atom.

Electrons are negatively charged and reside in a hole. When these electrons are removed, they leave a positive hole. Thus, the electron and the hole bond are like a negative and positive charge combination: equal and opposite.

CONDUCTION OF ATOMS

No electrons can flow unless they are free to do so. Some atoms will be added to the insulator atom structure that have either "1 more than" or "1 less than" 4 electrons in their valence ring. This means adding atoms that have either 3- or 5-valance electrons (outer rings). The structure change provides an off-balance.

Figure 3 shows atoms having 3 and 5 electrons which will be added to the 4-electron silicon base material.

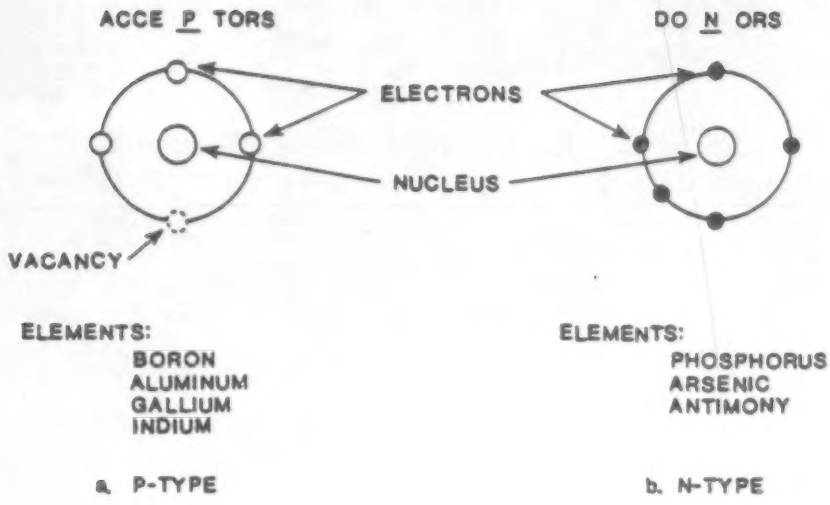


Figure 3. Impurity Atoms.

So that these atoms may be identified further, those atoms having only 3 electrons in the outer ring will be called P-type, and those having 5 electrons will be called N-type.

P-Type Atoms

Atoms having only 3 electrons, as compared to 4 electrons, could accommodate an additional electron. This is shown as the vacancy, and this vacancy has a positive charge. The vacancy can then become a location into which an electron can move temporarily if an outside force causes it to move.

N-Type Atoms

Atoms having 5 electrons, as compared to 4 electrons, have only one electron they can share or give up. This electron can move into the vacancy created in the P-type atom if an external force causes it to move and if the N-type and P-type atoms are bonded together.

The process of forming the P- or N-type material, known as doping, is achieved by a heating process known as fusion.

Combined Atoms

To form a semiconductor material, either the P or N atoms are added in small quantities to the 4-electron germanium or silicon atoms. This results in a primary silicon material with only small quantities of either P-type or N-type atoms.

Formation of the 4-_3 Combination (P-Type Material)

When semiconductors are constructed, either silicon or germanium is used as the foundation, and P-atoms or N-atoms are added. When P-atoms are added, the material thus formed is called a P-material. When the N-atoms are added, it forms an N-material. Figure 4 shows a P-material formation. Note the vacancy created when the 4-electron atoms and the 3-electron atoms are mixed.

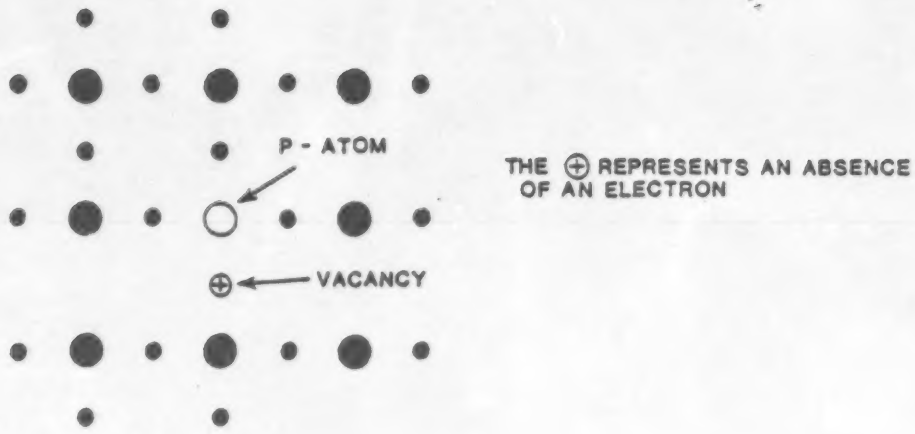


Figure 4. P-Type Material.

Formation of 4_5 Combination (N-Type Material)

Instead of adding atoms with 3 electrons, atoms with 5 electrons are added. The formation called N-type material yields extra electrons to the end product. Figure 5 shows the molecular structure formed from a fusion process. Note the additional atom created when the 4-electron atoms and the 3-electron atoms are mixed.

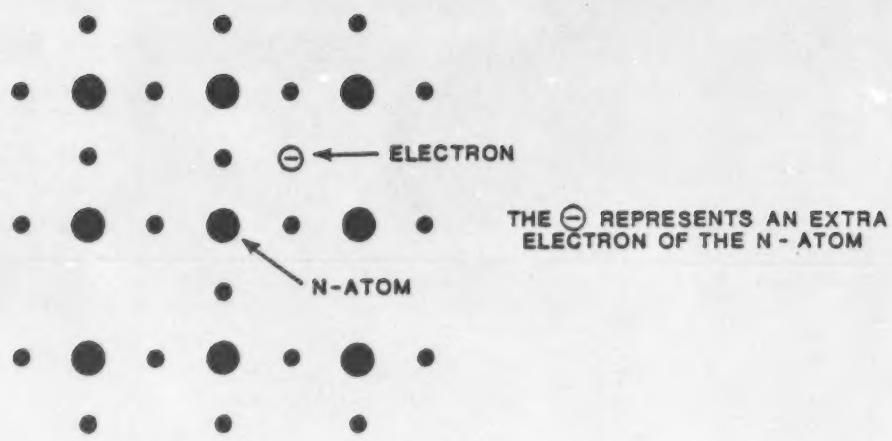


Figure 5. N-Type Material.

Conduction of P- and N-Type Materials

When the (+) and (-) conditions are created, either can be moved in a predetermined direction which is determined by the type of material and the polarity of the battery or external voltage source. In the creation of the material, the entity in abundance becomes the item moved by the battery. The abundant entity is usually called the majority carriers for forward current flow. Any flow of current in the reverse direction is called minority carriers and is always opposite in charge polarity. Figure 6 shows the movement (flow) of majority and minority carriers.

Particular attention should be given to the flow of current. The rules of current flow are not violated in the application. Note that majority current flow is far greater than minority current flow in either type of material. It should be obvious that the battery causes majority carrier movement.

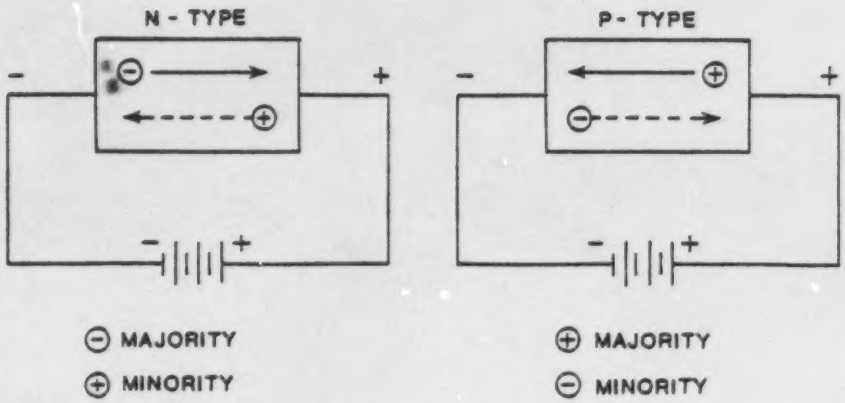


Figure 6. Flow of Majority and Minority Carriers in N- and P-Type Material.

Not so obvious is the cause of minority carrier movement. In earlier pages of this module, heat was said to have adverse effects on semiconductors. In this instance, heat is the energy that causes minority carrier movement. There is no such thing as a material that is perfect, and imperfections, in this case, occur in the presence of unwanted electrons or holes that are not bound to the material. Heat in the P- or N-type material releases carriers of unwanted polarity. These are the minority carriers.

FORMATION OF THE P-N JUNCTION

To create a basic solid-state device it is necessary to bond together a P- and N-section creating what is known as the P-N junction. When a battery is connected to the P-N device, a majority current is caused to flow in one direction only. With no battery connected, no current can flow – even though the P-section has extra holes and the N-section has

extra electrons. Figure 7 displays the condition without a battery.

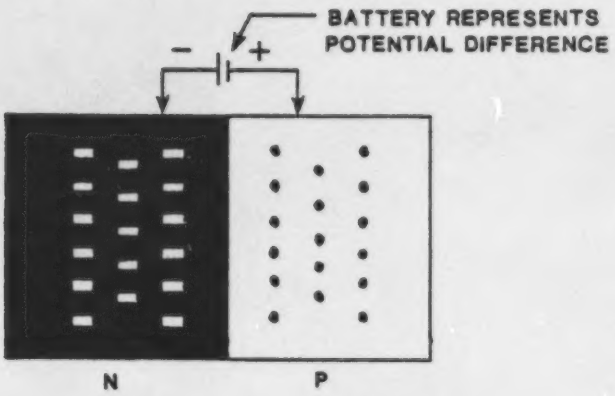


Figure 7. P-N Junction – No Battery.

Figure 7 shows the condition of the N- and P-section. The N-section shows an abundance of free electrons which are repelled and held back from the junction by the electrons of the P-section. The P-section shows an abundance of holes which are repelled and held back from the junction by the holes of the N-section. The net result is an N-section being negative in polarity and a P-section being positive in polarity. Because there is a difference in the number of electrons between the two sections, a potential difference (represented by a battery) exists internally within the formed P-N junction. (No battery is physically there.)

Figure 8 shows what takes place when an external battery is connected to the device.

In Figure 8a, the battery is connected so that no majority current will flow. The potential difference is made greater between the P- and N-section when the external battery is present so that the barrier between the two is greater

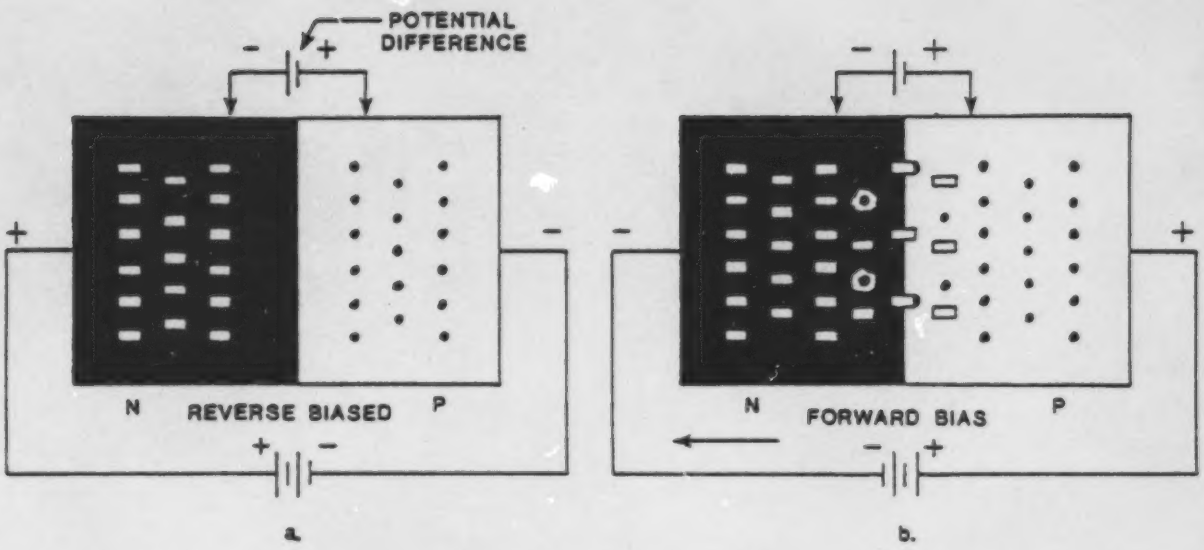


Figure 8. P-N Junction – With Battery.

(has a greater resistance). The battery reverse biases the P-N device (Figure 8a).

Figure 8b, on the other hand, causes a flow of majority carriers in both the N- and P-section. It should be realized that the potential difference across the junction is decreased to near zero – so the resistance is also reduced to a very low value – allowing current to flow between sections.

A clarification of current flow is important at this point. A battery provides electrons as a current flow. Moreover, the N-section provides an abundance of electrons that aids current flow. Electrons are the only items that flow out of the P-N device to the external circuit where the battery is located. The holes in the P-section can be considered as vacant locations that an electron may fill and again vacate as it migrates through the P-N device. In Figure 8b, electrons are leaving the battery negative terminal and entering the N-section. Along with electrons of the

N-section, the battery electrons migrate through the barrier, into and out of the holes in the P-section, and return to the positive terminal of the battery.

If the battery were reversed (as in Figure 8a) no current could flow. Thus, this device is a one-way path to the flow of electrons. If the battery were replaced with an alternating source, current would flow during either the positive or negative alternation, depending on the connection to the P-N device.

DIODES

The P-N device illustrated in Figure 8 is actually a practical diode. It can be used for several electronic applications, some of which are listed as follows:

- Rectifier.
- One-way switch.
- Regulator.
- Voltage-variable capacitor.

Rectifiers

As a rectifier, the diode rectifies an a.c. current flow to a pulsating d.c. current flow. Figure 9 shows this condition. In this example, the device symbol commonly found in diagrams is used. Note: During proper operation, current always flows from left to right against the arrow.

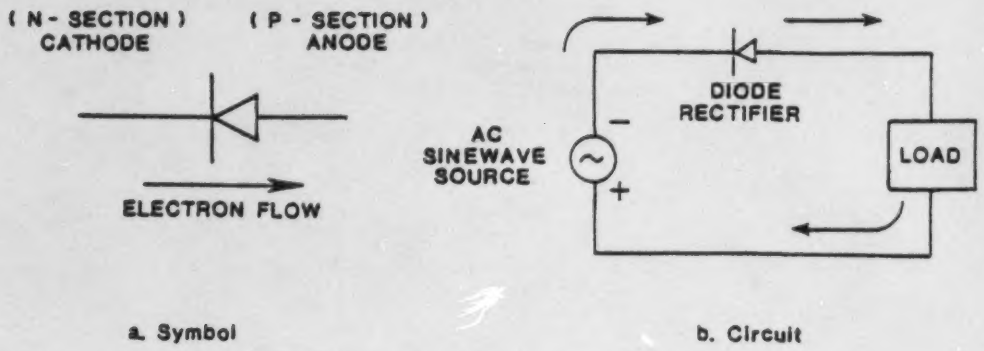


Figure 9. Diode Rectifier.

If current flows during negative alternation of the generator, the top of the generator is negative and the bottom is positive. Current will then flow clockwise (Figure 9b). When positive alternation occurs (because the top of the generator is positive and the bottom is negative), no current can flow because of the makeup of the diode.

Figure 10 shows a current flow graph of the common diode. This graph shows that current will flow easily after the barrier potential difference is overcome. As long as a potential of the proper polarity is attached to the diode, it will conduct. Reversing the battery or source (as long as it is not greater than the diode will withstand) will not allow current to flow. The result of the back, or reverse voltage, becoming too great is shown on the graph as avalanche current. This can cause permanent damage to the diode, resulting in a short circuit and, possibly, smoke and fire as well. In addition, if the diode is placed backwards in the circuit, permanent damage will take place within the diode because this also will result in a short circuit.

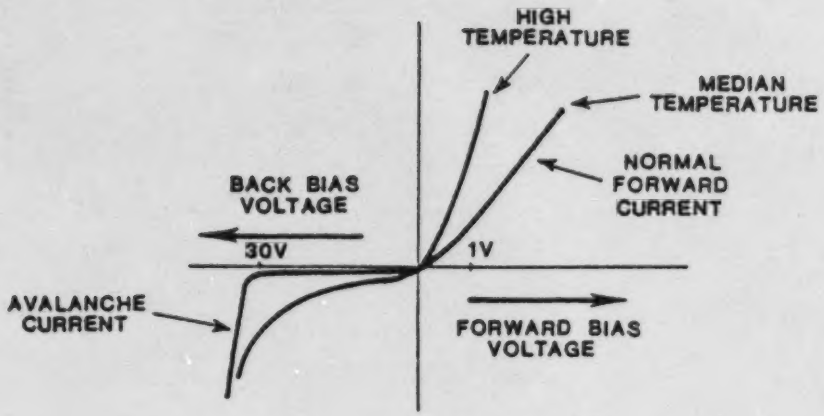


Figure 10. Standard Diode Rectifier.

One-Way Switches

Diodes can be used as a one-way switch. Some electronic applications require a signal coming in with nothing going out. This concept is much like an animal trap where the "once in-must stay in" principle applies. Figure 11 illustrates the principle.

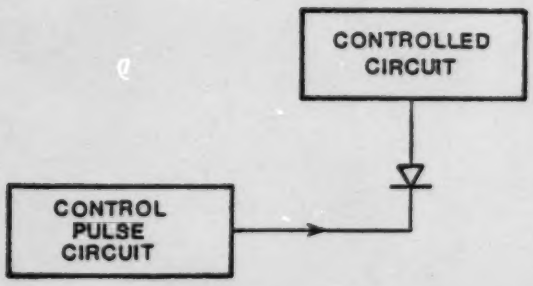


Figure 11.
Diode Switch.

In this block diagram, signals or currents flowing within the controlled circuit are not permitted to pass into the control pulse circuit. However, the proper polarity pulse from the control circuit is permitted to flow through the diode and into the controlled circuit.

Regulators

A special diode, called a Zener diode, utilizes the avalanche characteristic of a semiconductor device. The diode is made to break down at a specific voltage value when it is applied during nonconduction. Figure 12 explains this condition.

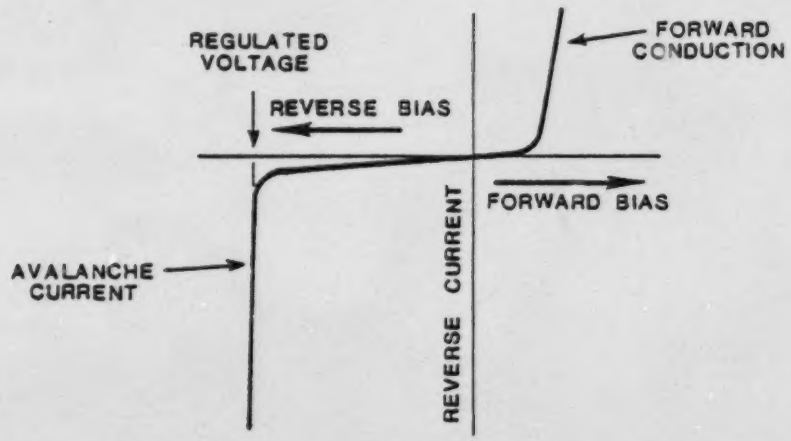


Figure 12. Zener Diode Response Curve.

The Zener diode is placed in the reverse position for proper operation. When a voltage equal to the breakdown value is applied to the diode, it will conduct avalanche current, acting as a near complete short for any voltages

greater than the breakdown voltage. This reaction "locks in" a voltage drop across the diode that remains constant in value. Figure 13 shows a practical application.

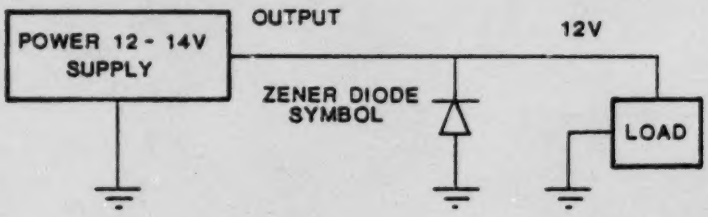


Figure 13. Zener Application.

Although the power supply output is a range from 12-14 volts d.c., the Zener locks in the load voltage at 12 volts. Thus, the voltage applied to the load is regulated.

Voltage-Variable Capacitors

Another semiconductor used in electronic equipment for both frequency-modulation and frequency-control is the voltage-variable capacitor, or varactor. This device is constructed to emphasize the change in capacitance that results in changes in the width of the barrier, or junction, of the diode. Much like a capacitor, the left and right sides of the junction act as the plates of the capacitor; whereas, the region in between becomes the dielectric. Changing the potential difference across the junction changes the distance between plates, thus changing the capacitance value of the diode. Figure 14 shows the junction area and illustrates how it changes width.

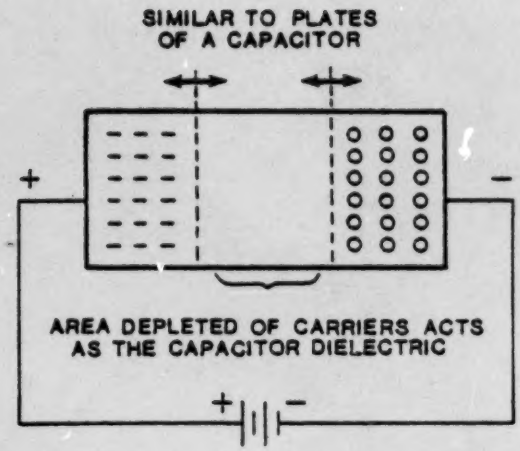


Figure 14. Varactor for Dielectric Changes.

If the diode is placed in the circuit in parallel with a coil, the frequency of the LC network can be varied as the capacitance value of the diode is changed. Figure 15 shows a practical LC circuit.

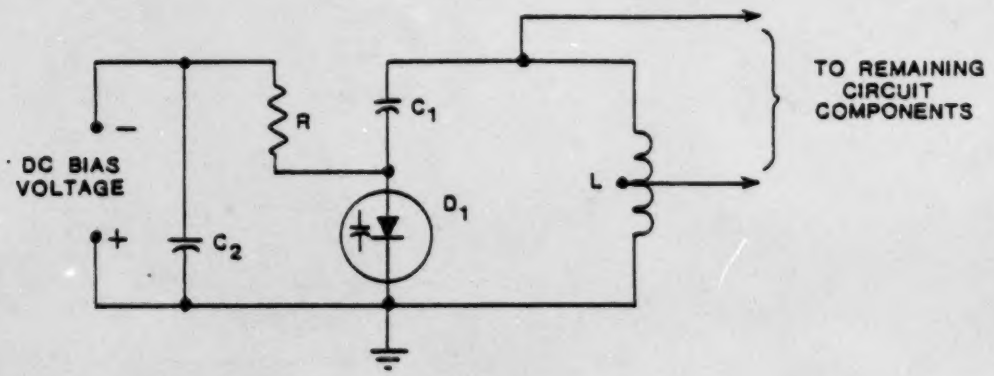


Figure 15. Varactor Circuit.

C_1 and the diode are in parallel with L, creating a parallel LC tank circuit. C_1 and C_{D_1}, being in series, add as their reciprocal adds. Changing C_{D_1} changes the total

C value and, thus, the resonant frequency of the tank circuit. C_{D_1} is changed by changing the d.c. bias voltage.

DIODE TESTING

Standard rectifier diodes can be checked with the use of an ohmmeter. The RX100 or RX1000 scale will show the best results. With the test leads placed one-way across the diode, an almost infinite value can be recorded. Reversing the leads will yield a very low resistance.

BIPOLAR TRANSISTORS

The transistor uses two P-N junction diodes. The intent of combining junctions is to create a control section over the electrons that flow from one end of the transistor to the other. Figure 16 shows the formation of a NPN bipolar junction transistor.

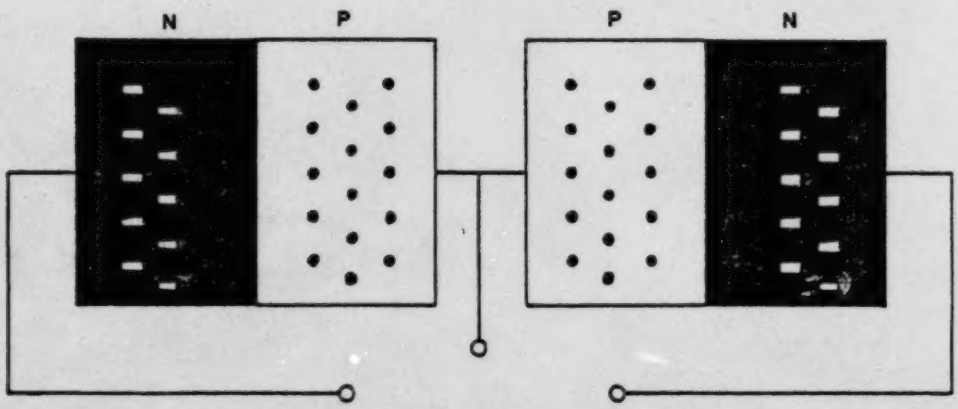


Figure 16. Formation of a NPN Bipolar Junction Transistor.

A PNP bipolar junction transistor, which is the complement of a NPN transistor, can also be formed.

At this point, it would be helpful to discuss how a transistor is made to control. In the study of tubes, it was learned that the input was made to control the output. In the case of transistors, the operation is quite similar. However, in most cases involving tubes, no current flows out of the control grid; yet current does flow normally out the control lead for the transistor. Figure 17 illustrates the leads of a transistor.

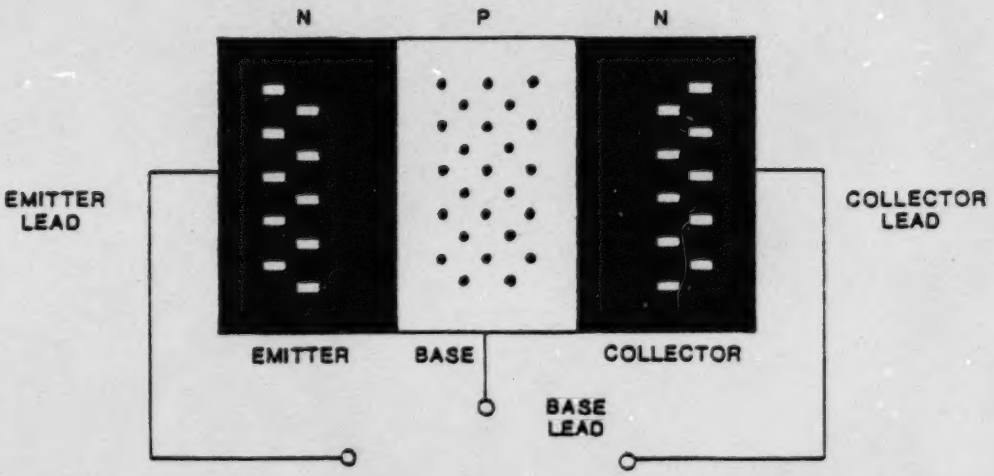


Figure 17. Bipolar Transistor Junctions (NPN).

To establish control, the junction between base and emitter will have applied to it a varying voltage which consists of a fixed d.c. voltage and varying a.c. signal voltage. It must be remembered that the control circuit is the input circuit. There must also be an output circuit. In the transistor, the output circuit is connected between emitter and collector. Figure 18 illustrates how all of this fits together (the NPN transistor stage).

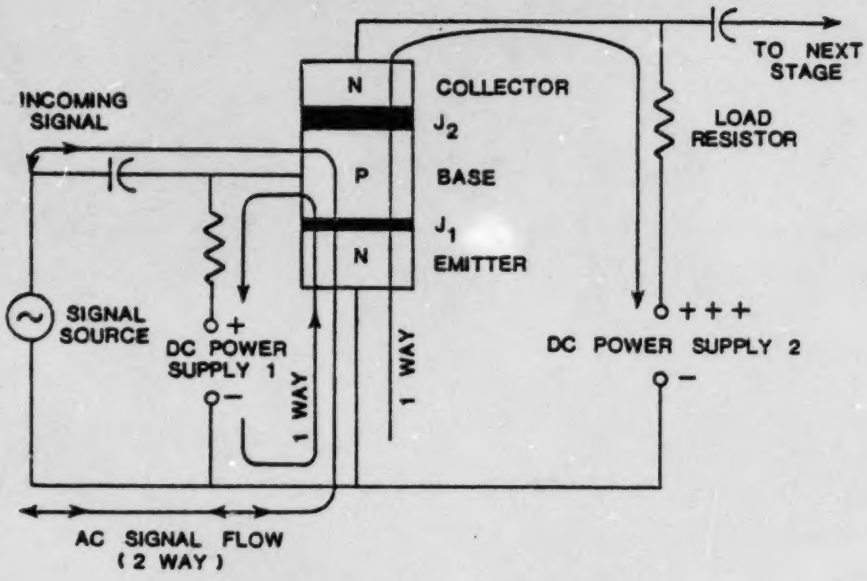


Figure 18. NPN Transistor Stage.

The junction between the emitter and base is forward-biased. In other words, as the signal becomes more positive during a positive alternation, the signal voltage adds to the fixed d.c. voltage and narrows the junction. When the junction becomes narrower, the resistance of this one-way barrier becomes reduced. Because there is less resistance here, more current can flow from emitter to collector. Inversely, when the negative alternation of the signal voltage appears, it subtracts from the fixed d.c. voltage (from the power supply). This causes the width of the emitter-base junction to increase, thus increasing its resistance. As a result, less output current flows from emitter to collector. It is important to note that the output power supply voltage is much larger in voltage than the input power supply voltage.

Moreover, a small change in input signal current controls a very large change in output current. Thus, compared to a tube, the transistor is a current-controlled device rather than a voltage-controlled device.

It was stated earlier that the PNP transistor is a complement to the NPN transistor. Figure 19 shows proper connections for the PNP transistor.

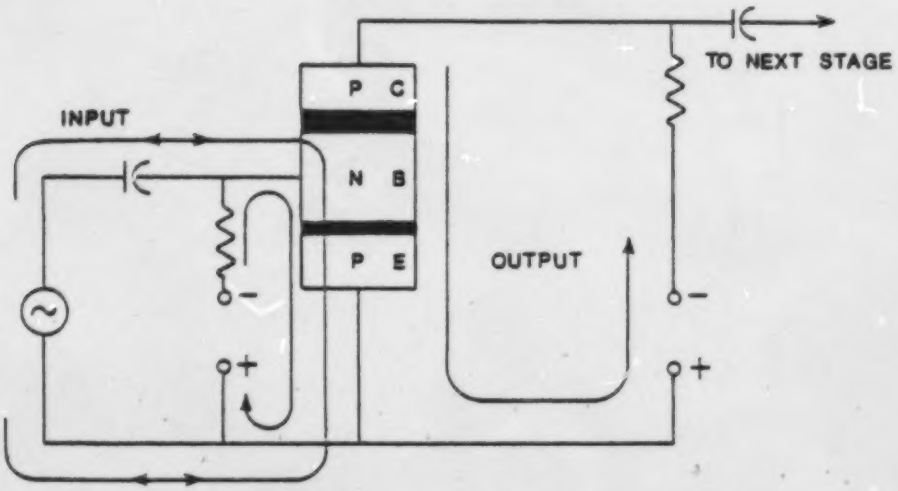


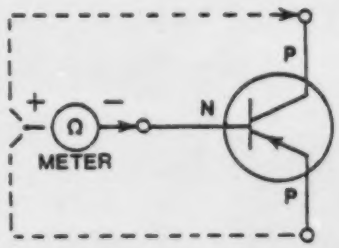
Figure 19. PNP Stage.

The major difference is the direction of current flow in the input and output circuits. Electrons comprise the majority carrier movement in NPN transistors; whereas, holes comprise the majority carrier movement in PNP transistors.

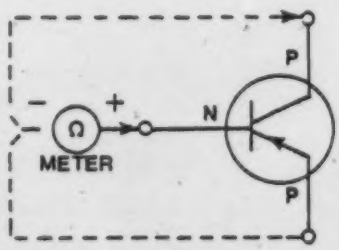
BIPOLAR TRANSISTOR TESTING

The ohmmeter is the basic test equipment for checking a transistor for GO or NO GO condition. Checking a transistor with an ohmmeter simply involves looking for unusually low or unusually high resistances. Both junctions must be checked for low and high resistances. This may be accomplished by reversing the leads for each junction. Figure 20 shows the proper way to check a PNP transistor.

In Figure 20a, the forward resistance is checked first. The positive ohmmeter lead is connected to the base. At the same time, the ground or negative lead is connected to the emitter and then to the collector. The result is a low resistance for B-E and B-C junctions. Figure 20b shows a reverse resistance check. In this test, the ground lead is connected to the base and, alternately, the positive lead is connected to the emitter and to the collector. This time, both tests will yield almost infinite readings.



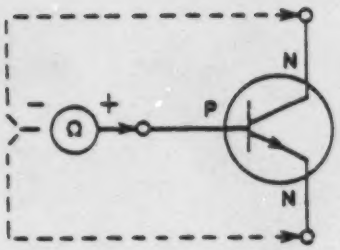
a. Forward Resistance Check



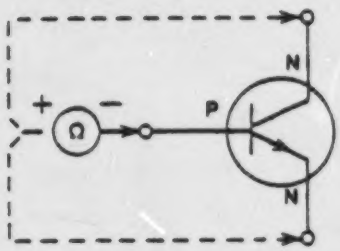
b. Reverse Resistance Check

Figure 20. PNP Transistor Testing.

Figure 21 shows the proper testing for a PNP junction transistor. The same basic procedure is followed here; however, in each case, the ohmmeter leads are reversed to yield a low and high resistance, respectively.



a. Forward Resistance Check



b. Reverse Resistance Check

Figure 21. NPN Transistor Testing.

The resistance values that one can generally expect in testing NPN to PNP transistors are listed in Table 1.

TABLE 1. TRANSISTOR RESISTANCE VALUES.

	NPN		PNP	
	Forward	Reverse	Forward	Reverse
Voltage transistors	300-500Ω	500,000 to 20 megΩ	300-500Ω	500,000 to 20 megΩ
Power transistors	200-400Ω	100,000 to 10 megΩ	200-400Ω	100,000 to 10 megΩ

IDENTIFICATION OF NPN OR PNP TRANSISTORS

Taking the proper steps to determine transistor type is important, since many are difficult to identify by numbers on the case. Below is a list that will be useful in identifying transistor types.

1. Determine lead identification (E, B, C).
2. Connect the ohmmeter to the base and emitter.
3. Obtain a low or high reading and note which lead is attached to the base.
4. Use Table 2 below to determine type.

TABLE 2. TRANSISTOR JUNCTIONS.

Resistance Reading	+ Ohmmeter Lead to Base	- Ohmmeter Lead to Emitter
High	PNP	NPN
Low	NPN	PNP

FIELD-EFFECT DEVICES

The development of the transistor has produced a solid-state device that operates much like a tube as far as electrical principles are concerned. Basically, there are two types of field-effect transistors: the junction FET and the insulated-gate FET. Because of construction, the second type is often called a metal-oxide FET.

JUNCTION FETs

FETs are unipolar because only one majority carrier is present throughout the device. This device is constructed with one path for current flow from one end to the other. The path, called a channel, has a lead attached to either of the ends much like a resistor. The channel also possesses a uniform resistance from one end to the other. The entrance end is called the source and the exit is called the drain.

Figure 22 shows the channel (shaded) which is made from an N-type material (4-_5) and a control segment that is located on either side of the channel and made from a P-type material (4-_3). The internal surface between the channel and control gate forms a junction. Notice that there is a P-type material located on either side of the channel. Both of these control surfaces are identical, and they act on the channel equally when they are used.

To control current flowing through the device in Figure 22, one must first hook up the voltage sources. Then, both gates (G) must be tied to the same voltage point, making this voltage negative. A voltage will then be applied between the source and drain. Figure 23 shows these connections with voltages and polarities.

The negative polarity applied to the control gates will repel electrons entering the channel at the source lead. Notice the source electrons are forced to pass through a narrower channel as they pass the gates. This narrowing action is controlled by the amount of negative voltage applied to the control gates. More negative voltage makes the channel even narrower. When the negative potential becomes so great that it actually repels all electrons from the source

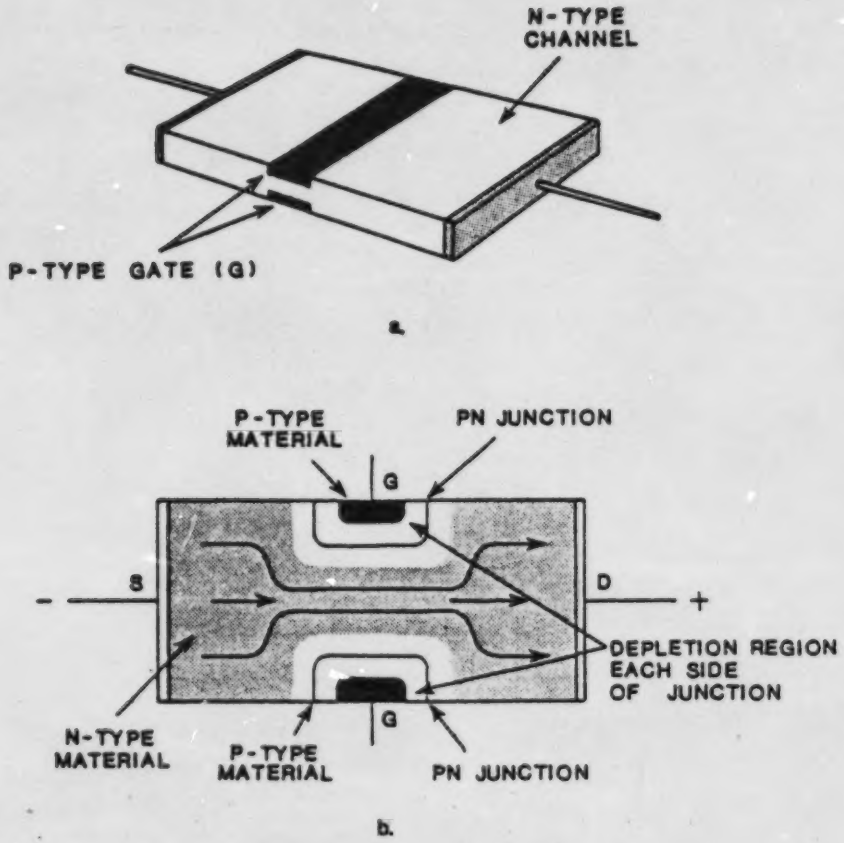


Figure 22. JFET Structure.

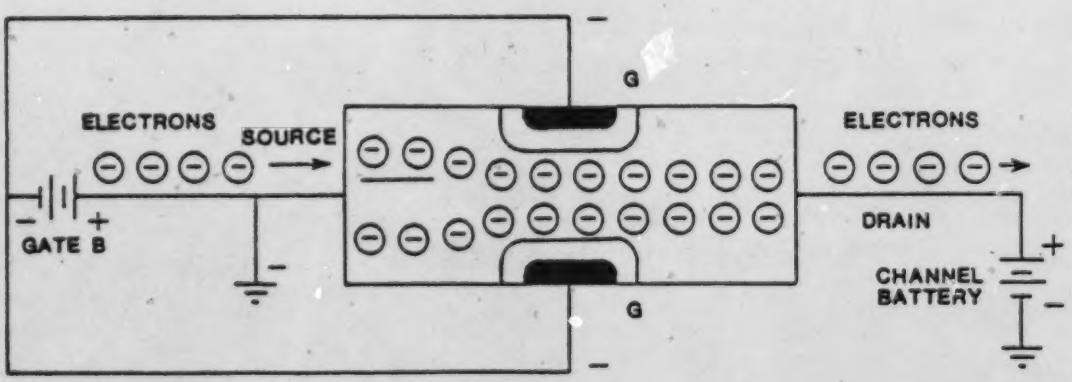


Figure 23. JFET Current-Flow Control.

and none reaches the drain, the result is called gate pinch-off potential. Notice the term "potential" is used, indicating that if the gate is always kept negative (as compared to the source) then no current can be attracted from the source and flow out the gate. Therefore, all current entering the source must flow out the drain. Changing the negative potential on the gates will control the electrons flowing through the channel.

This method of operation is similar to that of a water-pipe valve control. Another example is the operation of a canal lock used in boat channels. As a boat approaches, the gates are opened to permit the boat to pass. The size of the boat that can pass through the channel is governed by the gate opening.

For some applications, one of the FET gates can be tied to ground or some prefixed voltage more negative than the source and the other gate used for controlling the flow of current through the channel. Whichever method is used, a small change of voltage on the gate(s) causes a large change in current flow through the channel. Thus, a signal can be attached to the input gate(s), controlling the output current. Note here that the combination of the input signal and gate battery must never cause the gate(s) to be more positive than the source.

A N-channel and P-gate were used in the above example. However, FETs can also be constructed with a P-channel and N-gate. Under these conditions, battery polarities must be reversed. Figure 24 shows the polarity relationship necessary for both the N- and P-channel devices.

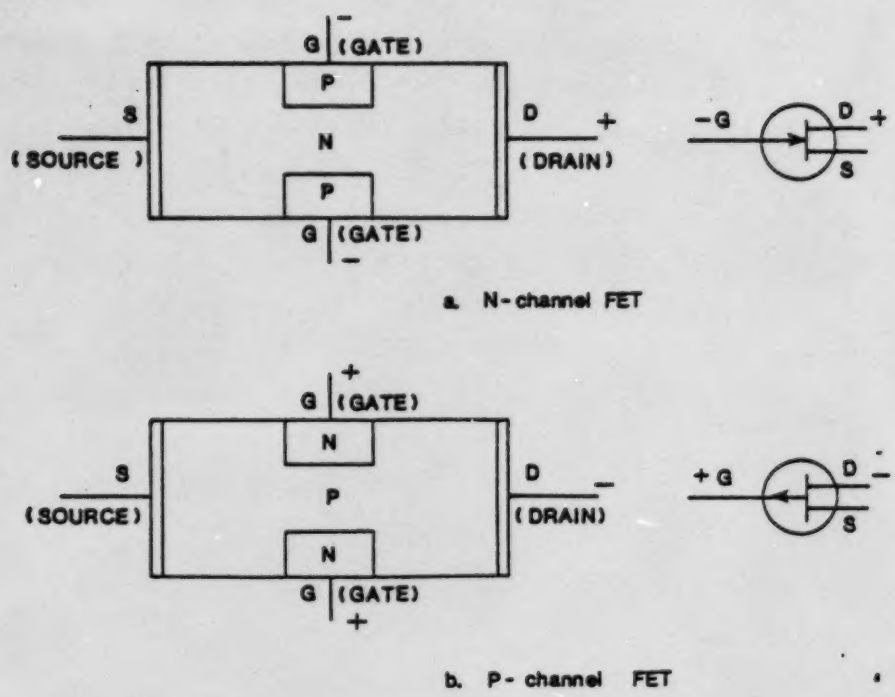


Figure 24. Polarity Relationship.

With the source lead being common, the N-channel device has the gate more negative and the drain more positive than the source. In the P-channel device, the gate is more positive and the drain is more negative than the source.

INSULATED GATE FETs

Depletion Mode

Another type of FET which does not have a P-N junction that must be reverse-biased is the depletion mode insulated

gate FET (IGFET). This transistor uses a gate that is physically and electrically insulated from the channel by a narrow layer of oxide material. The insulated gate is metal, which affords this device several advantages over the standard junction FET. Being insulated, current can never flow from the source lead through the channel and out the gate. In this device, the gate can, therefore, be made positive or negative (as compared to the source) without damage. In an amplifying device, this feature creates an enormous advantage. Figure 25 shows the construction and transistor symbol for the IGFET when the device is operated with the gate always more negative than the source.

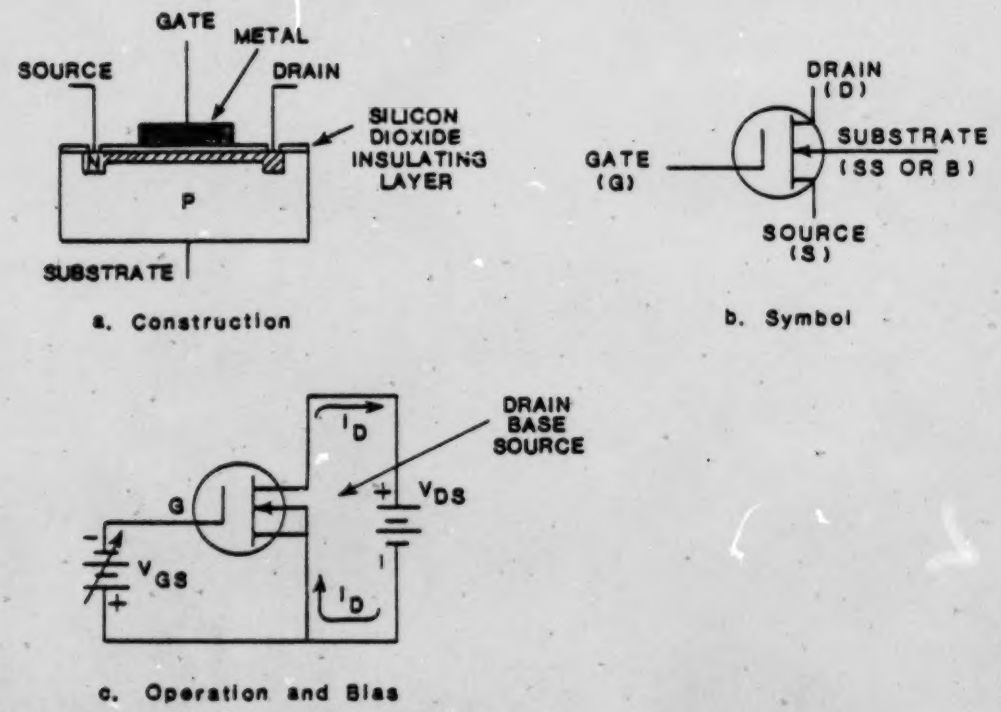


Figure 25. Depletion Mode IGFET.

The B lead shown is attached to the base or substrate of the device. Although the B lead can be connected differently, the common method is to attach the B and S leads together.

It must be noted that, even though the gate or input is insulated from the channel, arcing can occur if the potential difference between the gate and the source is too great. In order to avoid this possibility, care must be taken in designing a stage with this FET.

Enhancement IGFET

If the IGFET device is used so that the gate is sometimes operated "more positive" than the source, the external gate voltage supply must be reversed, as shown in Figure 26. This mode of operation is called the enhancement mode. The device is still a N-channel device, as is shown by the arrow pointing IN (representing N-channel).

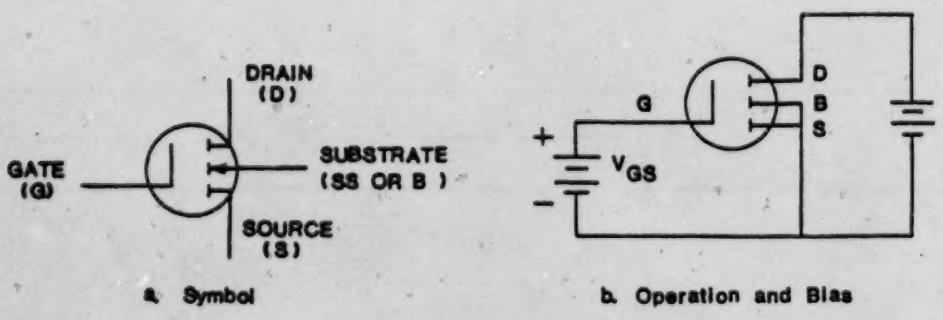


Figure 26. Enhancement Mode.

Furthermore, when the IGFET is operated in this mode, its symbol on a diagram has a broken line along the drain, base, and source (Figure 26).

As was the case with junction FETs, this device can be constructed with a P-channel. The voltage sources must then be turned around (in contrast to the N-channel type). The gates are made from a metal material, rather than a N-type material – which is possible because of an oxide layer. There is no junction in the IGFET.

CONFIGURATIONS

Transistors – whether uni-junction or bipolar – can replace tubes in many applications. They are operated in Classes A through C. Transistors can be configured in three basic ways, as can tubes. Table 3 compares the configurations of tubes and transistors.

TABLE 3. TUBES COMPARED WITH TRANSISTORS.

Tubes	Transistors		
	Bipolar	JFET	IGFET
Common Cathode	Common Emitter	Common Source	Common Source
Common Grid	Common Base	Common Gate	Common Gate
Common Plate	Common Collector	Common Drain	Common Drain

Figure 27 shows examples of bipolar and JFET transistor configurations for Class A stages. Because IGFETs are configured the same, these devices are excluded from the examples. Only NPN bipolar and N-channel unipolar devices are shown. In all cases, the supply voltages are reversed if PNP or P-channel devices are used.

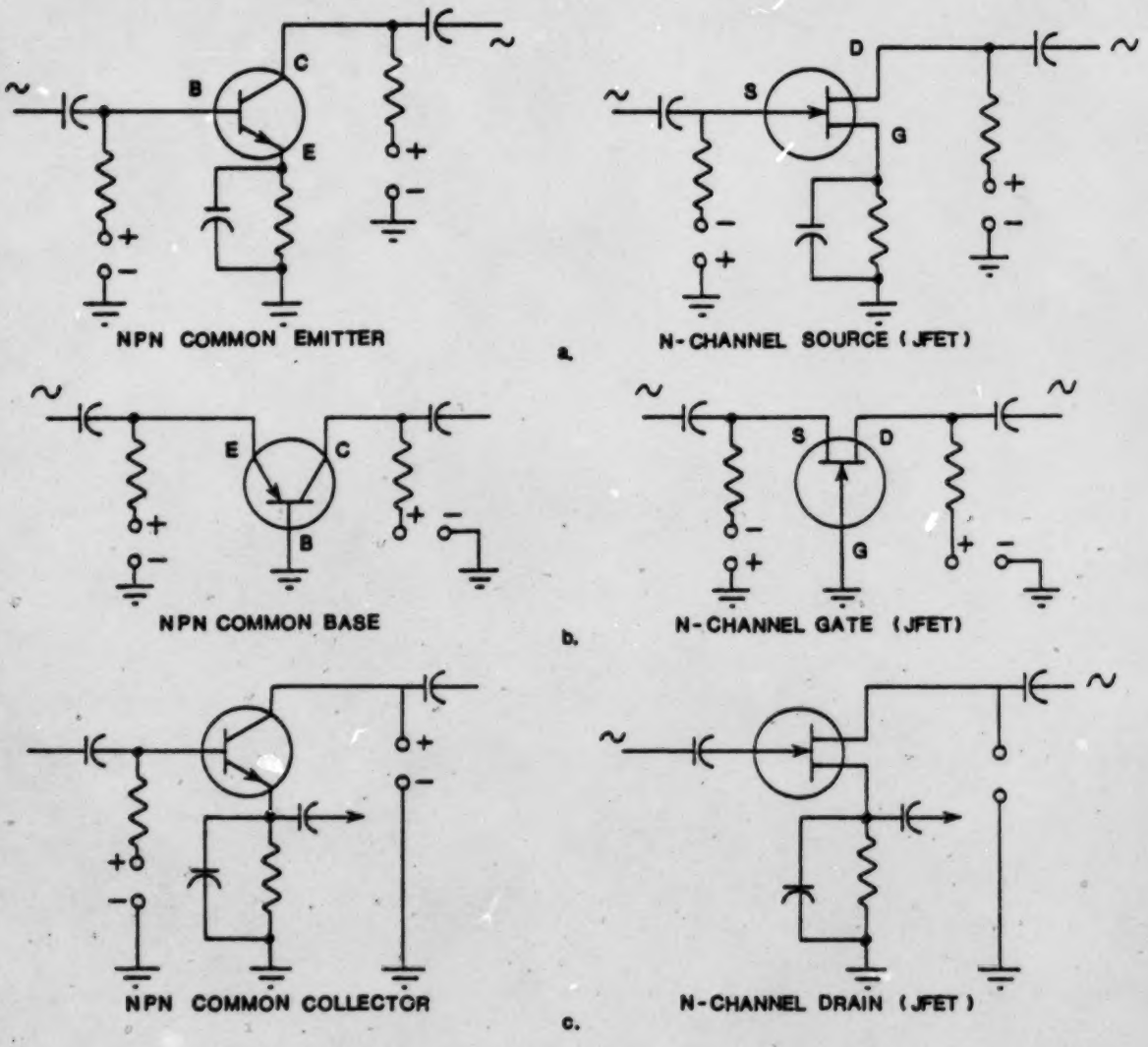


Figure 27. Class A Stages.

FET SAFETY PRECAUTIONS

IGFETs are very sensitive to static electricity that is emitted from the body. Caution must be taken not to touch the leads while handling these devices. When shorting clips are found on leads, they should not be removed until the device is installed and soldered in place.

JFETs and depletion-mode IGFETs can never have the gate made positive compared to the source. It is important to check manufacturer's data for maximum ratings to assure that voltages and currents remain within safe limits for all applications.

EXERCISES

1. Describe why there is a potential difference formed at the junction of a PN diode that has no external voltages applied.
2. Explain how to distinguish the difference between voltage and power transistors.
3. Explain why reversing a standard diode will cause a short circuit in many applications.
4. Using Table 1 as a reference, draw three Class A common emitter stages interconnected, showing the input and output resistances for each. Are these stage resistances matched?
5. Compare the characteristics of bipolar and unipolar transistors for the following:
   a. Junctions.
   b. Resistance of input to output.

LABORATORY MATERIALS

Laboratory 1

VTVM or FET meter with leads.
Oscilloscope (triggered).
20 volt d.c. power supply (regulated preferred).
Sine wave generator (1000 kHz).
Breadboard.
Hookup wire.
1-NPN transistor (TO-92 package).
1-100kΩ 1/2 watt potentiometer.
1-1kΩ 1/2 watt potentiometer.
3 - 30-35 microfarad tantalum-fixed capacitor.

1 - 1KΩ 1/2 watt fixed-carbon resistor.
1 - 4.5-5.0 kΩ 1/2 watt fixed-carbon resistor.
1 - 10kΩ 1/2 watt fixed-carbon resistor.
1 - 56kΩ 1/2 watt fixed-carbon resistor.

Laboratory 2

1 - ohmmeter with leads.
Components required:
1 - TO-92 package bipolar transistor (voltage).
1 - TO-3 or TO-66 package (power).

LABORATORY PROCEDURES

LABORATORY 1. BIPOLAR COMMON EMITTER TRANSISTOR CLASS A AMPLIFIER.

This experiment demonstrates the operation of a common emitter amplifier. The student is shown how to bias a bipolar transistor for a Class A operation. Voltage gain is calculated with an input sinusoidal waveform. The importance of an emitter bypass capacitor is emphasized and the results of increased output load are shown.

1. Construct the diagram shown in Figure 28 on a breadboard. IMPORTANT: Do not turn on the power supply until the instructor has checked the wiring and confirmed that it is safe.
2. Prewarm the voltmeter and oscilloscope for at least 5 minutes before using them.
3. Before turning the power supply ON, adjust the voltage control to zero volts.

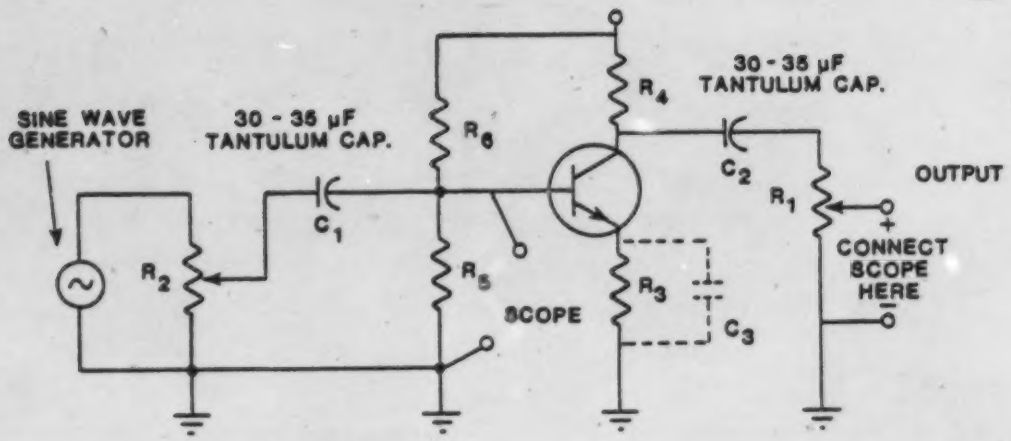


Figure 28. NPN Transistor Circuit.

4. Attach the (+) lead of the voltmeter to the collector. Attach the (-) lead of the voltmeter to (- neg) or ground.
5. Attach the (+ pos) lead of the power supply to the top of R_4. Attach the (- neg) lead of the power supply to ground.
6. With the meter connected as in Step 4, adjust the power supply voltage control so 10 V d.c. is read on the meter. Make sure the meter is set on the proper function and range.
7. Adjust the sine wave generator to 1kHz.
8. Adjust R_1 fully clockwise.
9. Adjust R_2 fully clockwise.
10. Connect the oscilloscope to output, as shown in Figure 28.
11. Using the triggered oscilloscope, measure the P-P waveform voltage and record the result in Data Table 1(B). (Make certain the scope is properly calibrated before using.) Plot the waveform on graph 1(B) below Data Table 1(B).

12. Reduce the input signal by turning R_2 counterclockwise 1/2 of the full rotation of the control.
13. Enter P-P waveform voltages in Data Table 1(A) and the output waveform on graph 1(A).

DISCUSSION 1:

Steps 1-13 show stage gain for two different settings of input signal. To determine approximate gain, divide E_{out}/E_{in}. Enter the result in Step 16a.

14. Turn the power supply OFF.
15. Add a 30-35 μF capacitor across $R_3(C_3)$. Repeat steps 1-13. Place the results in Data Table 1(C) and graph 1(C) for the input and output signal voltages and waveforms.

DISCUSSION 2:

Calculate stage gain <u>with</u> C_3 in place, using Data Table 1(C) and graph 1(C). Enter the results in Step 16b.

16. Stage gain calculated, showing effects of C_3:

$$A = \frac{E_{out}}{E_{in}} = \_\_\_\_\_$$

a. without C_3

$$A = \frac{E_{out}}{E_{in}} = \_\_\_\_\_$$

b. with C_3

Note: Re-adjust R_2 to fully clockwise position before continuing.

17. Adjust R_1 (output load) to 1/2 full clockwise and record oscilloscope results in Data Table 1(D) and graph 1(D).
18. Adjust R_1 (output load) to fully clockwise and record oscilloscope results in Data Table 1(E) and graph 1(E).
19. What effect does an increased output load have on the following:
    a. Input signal _____.
    b. Output signal _____.
20. What causes these results?

LABORATORY 2. TESTING BIPOLAR TRANSISTORS AND IDENTIFYING PNP TO NPN TRANSISTORS.

In this experiment, the student learns the testing procedure (using a multimeter) for NPN and PNP bipolar transistors. An ohmmeter is used to test the bipolar transistors. Two ranges are usually used: Rx10 for low resistances and Rx1mΩ for high resistances.

1. First, test the TO-92 package transistor. The lead identification must be determined for the transistor before proceeding. With assistance from the instructor, look up the TO-92 lead diagram in a transistor data book. Depending upon the transistor chosen, it could be a NPN or PNP. The lead arrangement will not change from one TO-92 type to the other. The package style determines the lead arrangement. If further data is needed beyond this lab concerning the transistor, refer to a manufacturers characteristic manual.

2. Use Table 1 of the text to determine transistor type, fill in Data Table 2 after testing the transistor with the ohmmeter. (Refer to text for testing procedures if necessary.)
3. Now, test the TO-3 or TO-66 packaged transistor. Following Figure 3, locate the leads E, B and C. Connect the meter and test the transistor (according to the procedures given in the text of this module). Place the measurements in Data Table 2.

DATA TABLE 1. BIPOLAR COMMON EMITTER TRANSISTOR CLASS A AMPLIFIER.

	Input	Output
TABLE 1(A) Step 13 R_2 1/2 clockwise	P-P Voltage	P-P Voltage
	Waveform ov _____ Graph 1(A)	Waveform ov _____

Data Table 1. Continued.

	Input	Output
TABLE 1(B) Step 11 R_2 fully clockwise	P-P Voltage	P-P Voltage
	Waveform ov _____ Graph 1(B)	Waveform ov _____

Data Table 1. Continued.

	Input	Output
TABLE 1(C) Step 15 R_2 1/2 clockwise	P-P Voltage	P-P Voltage
Graph 1(C)	Waveform ov _____	Waveform ov _____

Data Table 1. Continued.

	Input	Output
TABLE 1(D) Step 15 R_2 fully clockwise	P-P Voltage	P-P Voltage
	Waveform ov _____	Waveform ov _____

Data Table 1. Continued.

	Input	Output
TABLE 1(D) Step 17 R_2 1/2 clockwise	P-P Voltage _____	P-P Voltage _____
Graph 1(D)	Waveform ov _____	Waveform ov _____

Data Table 1. Continued.

	Input	Output
TABLE 1(E) Step 18 R_2 fully clockwise	P-P Voltage	P-P Voltage
Graph 1(E)	Waveform ov _____	Waveform ov _____

DATA TABLE 2. TESTING BIPOLAR TRANSISTORS.

	NPN		PNP	
	Forward Resistance	Reverse Resistance	Forward Resistance	Reverse Resistance
1. TO-92				
2. TO-3 or TO-66				

REFERENCES

Boylestad, Robert and Nashelsky, Louis. Electronic Devices and Circuit Theory. Englewood Cliffs, NJ: Prentice-Hall Publishing Co., 1978.

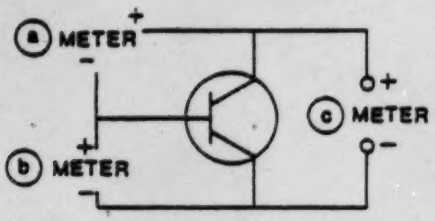
Evans, Charles H. Electronic Amplifiers. Albany, NY: Delmar Publishing Co., 1979.

TEST

1. Name four advantages and two disadvantages of bipolar transistors over tubes.

2. State the proper number of valence ring electrons in the following:
   a. P-material.
      (1) Silicon _____.
      (2) Impurity _____.
   b. N-material.
      (1) Silicon _____.
      (2) Impurity _____.
3. How many forward biased junctions are there in a PNP (operating Class A) transistor?

4. When testing a bipolar transistor, state the proper resistance (high or low) for the following:



a. _____.
b. _____.
c. _____.

5. How many junctions does an enhancement mode IGFET have?

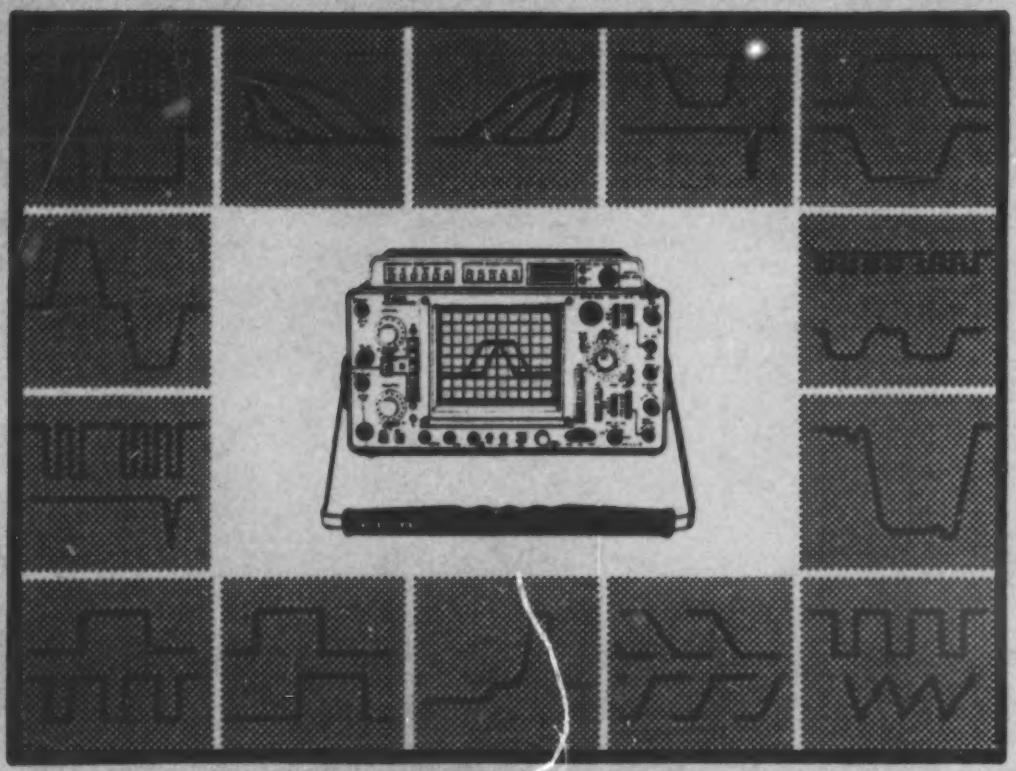
6. What happens when the gate of a depletion mode P-channel IGFET is made positive?

7. From all information given, which of the following should be able to operate with lower voltages?
   a. JFET _____.
   b. IGFET _____.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-04

INTEGRATED CIRCUITS

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4800 LAKEWOOD DRIVE, SUITE 5
WACO, TEXAS 76710

INTRODUCTION

Major advancements have been made in solid-state devices. Micro-miniature electronic components formed on a small "chip" create a small, neat package capable of performing the job that many separate discrete components once performed. Although integrated circuits (IC's) cannot replace all discrete applications, they are rapidly narrowing the gap. This module covers basic theory and stage application of analog IC's.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. State the advantages and disadvantages of IC's.
2. Discuss the capabilities of bipolar and MOSFET IC's and the limitations of each.
3. Name the different IC construction styles used and the applications for each.
4. Name and define the three stages in an operational amplifier.
5. State the use of an open-loop "op" amp and indicate whether it uses feedback.
6. Determine the output shape, amplitude, and phase of an inverted "op" amp compared to input.

7. Determine the output shape, amplitude, and phase of a noninverted "op" amp.
8. State whether the open- or closed-loop "op" amp reproduces without distortion.

THE IMPACT OF INTEGRATED CIRCUITS

True miniaturization has been achieved with the introduction of IC's. Great strides have been made to improve IC chips so that they continue to make inroads into the world of electronics. Both advantages and disadvantages accompany the production and use of these devices.

ADVANTAGES

The IC's major advantage is the size of the device and the space required for circuit implementation. These devices are now so small that they are no longer significant in the size of the equipment of which they are a part.

Construction of IC's makes them durable and reliable. The aerospace industry used IC's extensively in outer space applications. This use indicates longevity, since IC's are required to be in operation for many years. Many systems also employ complex circuits that are expected to operate without failure under adverse conditions.

Because of their size and construction, most IC's require little power to operate. As a result, less energy is used.

DISADVANTAGES

As with transistors, IC's are sensitive to heat and high voltages. Most IC's can operate in relatively warm environments; however, temperatures must be far lower than the temperatures of vacuum tubes. IC's operate at voltages below 50 volts, with most voltages below 20 volts. Because of low voltages, low currents flow through IC's. The end result is a low power output, with most IC's operating with an output power of 1 watt or less.

If an IC fails, it must be replaced; it cannot be repaired. All IC's are enclosed in a hermetically sealed package. It is useless to attempt to take this package apart; the circuit inside is so small that repair is impossible. Because of cost and reliability, replacement of IC's is economical and poses no problem.

TYPES OF IC's

As with transistors, both bipolar and metal oxide semiconductor (MOS) IC's have been created. While the electronic theory is the same for constructing discrete devices and IC's, the method of creating individual components inside the chip is different from parallel approaches for discrete devices. Construction methods for bipolar and MOS devices will now be discussed.

BIPOLAR IC's

Bipolar IC's and discrete circuits use similar components. Figure 1 shows a bipolar IC incorporating a common emitter transistor stage.

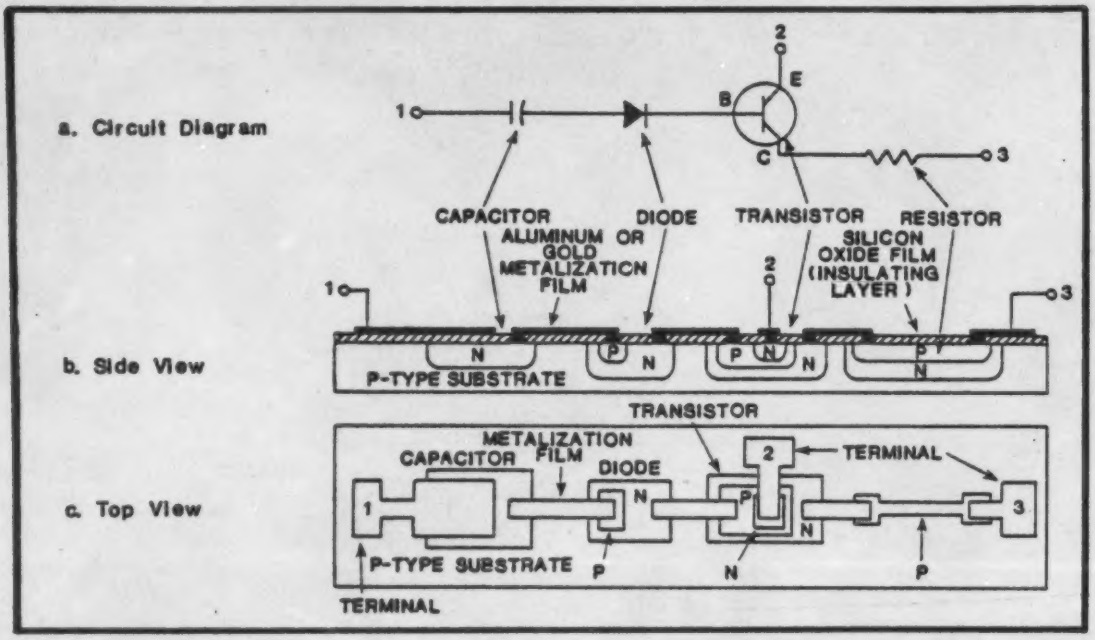


Figure 1. Bipolar Construction.

It is easy to construct transistors inside IC's. More difficulty is realized in forming capacitors and small resistors, where if either is of a large value or voltage, it is excluded from being placed inside. Moreover, transformers are not a part of internal components.

MOS IC's

Insulated gate field-effect transistors (FETs) are also incorporated in MOS IC's. The construction here is similar to the construction for discrete IGMOSFETS (insulated gate metal oxide semiconductor field-effect transistors). These devices are combined with capacitors and resistors, as were bipolar IC's. Figure 2 shows how an IGMOSFET is formed in the IC.

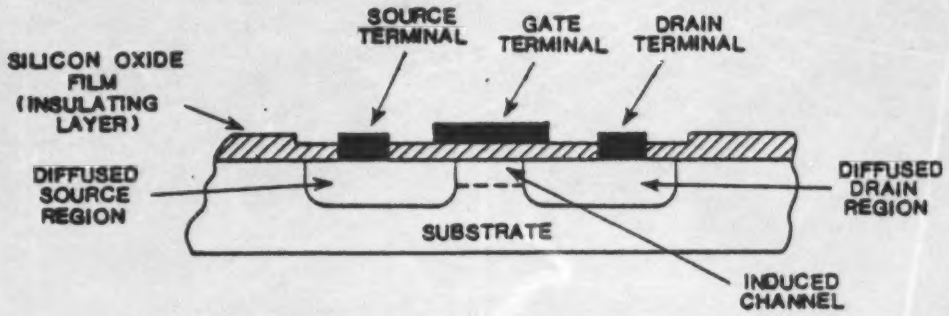


Figure 2. Part of an IGMOSFET IC.

One advantage with MOS technology is that a MOSFET can be formed in a smaller space than a bipolar transistor. This is one of many reasons for the IC's popularity.

OTHER STYLE IC's

Thick Film

Whether bipolar or MOS IC construction is used, these devices can be formed in layers much like one story of a house placed (and insulated) on top of the other. Different components are arbitrarily placed in different layers. When multilayer construction is employed, the device is called a thick-film IC, as compared to thin-film IC's. More components can obviously be placed in the device, but more heat will be internally generated as a result.

Hybrid IC's

Hybrid IC's are created by combining various combinations of layers, and possibly discrete components, in one package. A variety of packages, depending upon need, can be produced. Figure 3 shows an example of a hybrid IC.

The hybrid device may have an IC within an IC, as shown in Figure 3. The monolithic IC shown is constructed similar to a standard bipolar transistor. Individual devices are interconnected by flat wires much like that used on printed circuit boards in electronic equipment.

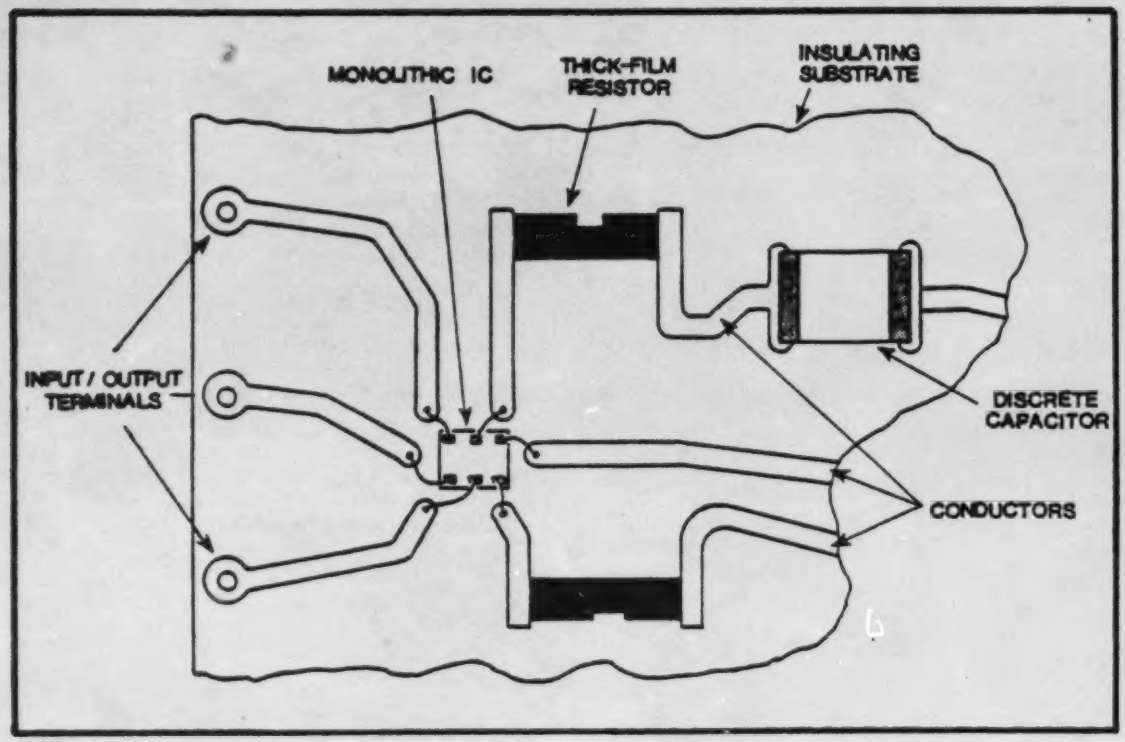


Figure 3. Hybrid IC.

APPLICATIONS OF ANALOG ICs

IC's are used in two specific categories of electronics. In almost all cases, IC's can replace transistor stages that exist in analog circuits. These packages are smaller and capable of almost as much power output as the discrete devices. The second category is digital circuits. Developments during the past 15 to 20 years have produced a multitude of digital IC chips.

Analog IC's will be discussed in this module. Digital IC's will be covered in a later module. It is important to note, however, that digital electronics use is broader than analog use in the application of IC's.

In analog electronics, IC's are usually used in amplifiers and oscillators, with use in amplifiers most common. This use has been realized in consumer products, particularly those used for entertainment. Television monitors and sound equipment utilize many of these devices. These examples incorporate several stages inside one chip, such that an entire section of a system has perhaps 8 or 10 stages. In these cases, chips are specialized, rather than universal. Each manufacturer develops a version to enhance originality and product security. Several of these are listed:

- Intermediate frequency amplifier.
- Sound amplifier (including detection).
- Color processors.
- Automatic gain chips.
- Preamplifiers.

These chips can be purchased from manufacturers with relative ease. More data can be obtained from manufacturer data books produced by Motorola, RCA, Texas Instruments, Sprague, General Electric, and others.

This module will cover universal analog chips that can be incorporated in different circuits to accomplish specific jobs. Operation amplifiers is one example. Students will perform a laboratory exercise at the end of this unit that further displays characteristics of the "op" amp.

OPERATIONAL AMPLIFIER

In the analog world, most amplifiers reproduce all or part of the signal placed on their inputs. The operational amplifier device can amplify either d.c. or a.c. signals, and provides a substantial gain from input to output if desired. This gain can be controlled so that it can be zero or several thousand. External circuitry is added to control and provide the desired gain for each application of the device.

Figure 4 shows a typical "op" amp and the different packages in which it is enclosed. Figure 4a shows the diagram internally, while Figure 4b shows the symbol found on a system diagram. Figure 4c shows an IC package in which two IC's can be arranged, while Figures 4d and 4e have one IC. The IC package can be circular or rectangular, depending upon the manufacturer.

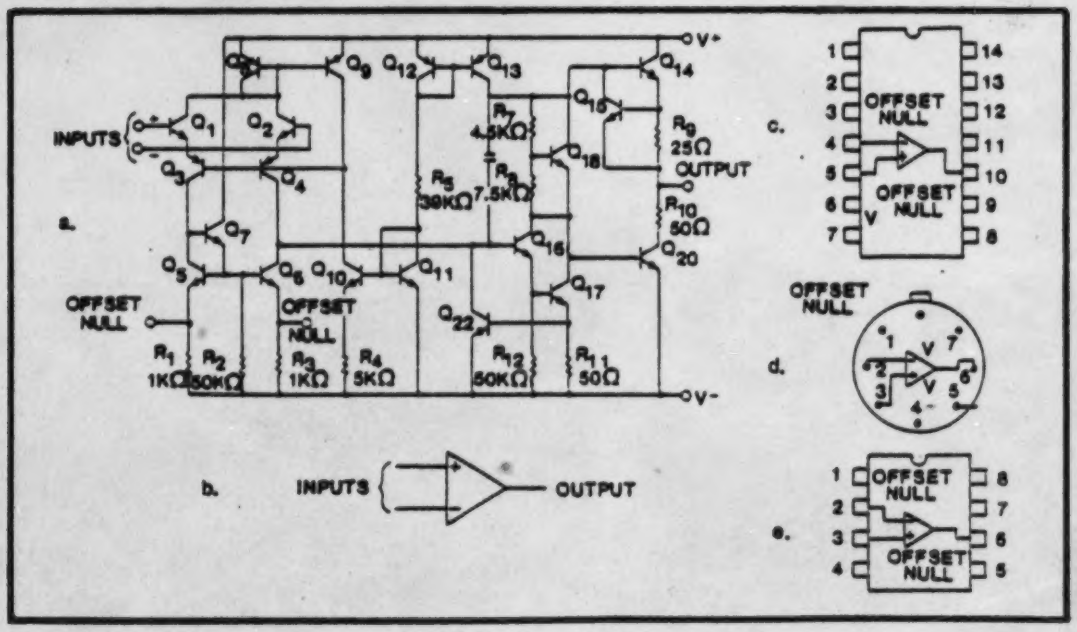


Figure 4. Operational Amplifier Diagram.

In most applications, maximum amplifying ability of the "op" amp is not used. One advantage in doing this is that stage stability is increased as a result. Stability reflects its ability to accurately reproduce the input signal at its output.

Note that this IC has two inputs and one output. Each input will be discussed and the general operation explained.

Figure 5 shows the basic internal stages of an operational amplifier.

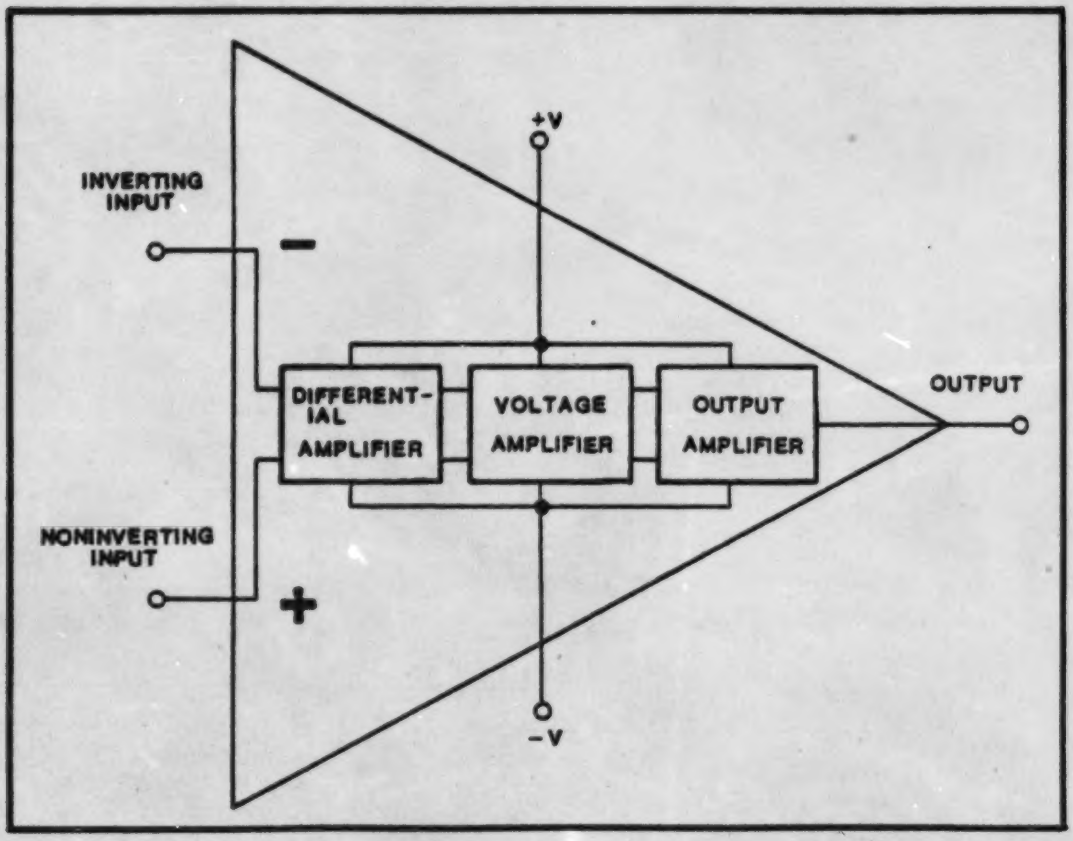


Figure 5. Operational Amplifier.

- Stage 1 – Differential Amplifier.

  This stage provides three advantages for good reproduction: noise rejection, high input resistance, and wide frequency response.

  Any signal can be accompanied by noise that comes either from external environmental sources or internal circuits. Either noise reaching the amplifier output, often a speaker, creates distortion. To reject this unwanted noise, two inputs are provided on the differential amplifier. Within the first few stages of the differential amplifier, the noise is canceled, leaving the desired signal. Unfortunately, not all noises are cancelable. However, the differential amplifier does provide rejection for common mode noise. Hum in the speaker is one noise in this category.

  The differential amplifier provides high input resistance to incoming signals applied. This assures that the "op" amp will not be a low resistance load on previous circuits that, as a result, increase system stability and energy drain. Because the voltage amplifier follows, the differential amplifier also provides a high resistance output.

  Most differential amplifier stages are d.c. coupled to the second stage, providing a frequency response from 0 Hz to many megahertz.

- Stage 2 – Voltage Amplifier.

  The voltage amplifier is a high gain stage – typically as high as 250,000. While this is a very good characteristic, instability can occur in high amplification levels. Thus, most applications use only part of this amplification. Almost all signal voltage increase is accomplished in this stage. Again,

frequency response is maintained because d.c. coupling is used in the voltage amplifier and the differential amplifier. For a review of d.c. coupling, refer to Modules ED-01, ED-02, and ED-03.

- Stage 3 – Output Amplifier.

  The major purpose of this stage is to provide a low output resistance so the "op" amp can drive (with a reasonable current flow) stages that follow. In some applications, this IC chip may drive another amplifier of some kind that provides power to an output load such as a speaker. In other cases, the IC chip may provide a signal to drive a display.

POWER SUPPLY REQUIREMENTS

This IC uses both positive and negative power supplies to allow a wider signal swing at the output. Most operational amplifiers use voltages ranging from 5 to 20 volts. The IC has pins to accommodate both power supplies, with ground being the common reference for the positive and negative sources.

CHIP USE

Figure 6 shows basic connections of the device. Although the hookup looks simple, the device may be used in several ways. The different modes are open-loop operation and closed-loop operation (inverting and noninverting configuration).

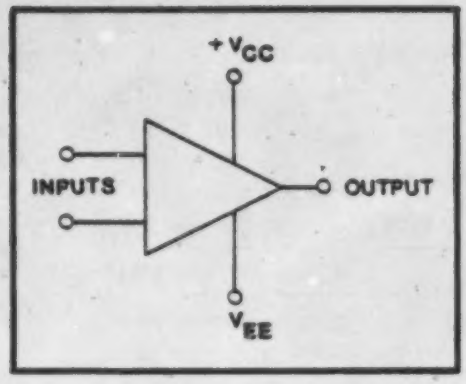


Figure 6. Operational Amplifier Basic Connections.

· Open-loop operation.

When the "op" amp is used in this arrangement, all device gain is utilized. Most applications do not use this type of connection, however. When used with an open loop, no signal is fed from the output back to the input. The result is a saturated amplifier in either the positive or negative direction. Figure 7 illustrates input and output of this device. Notice particularly the shape change from input to output.

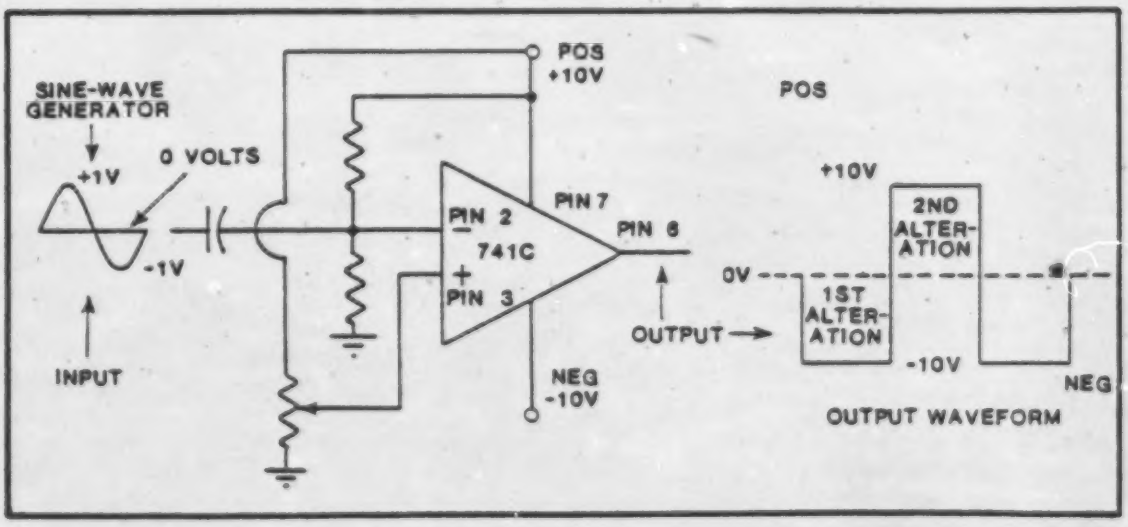


Figure 7. Simple Comparator (open loop).

When used in the open-loop arrangement, the only practical circuit is called a comparator. When the sine wave on the input goes positive, the output is driven immediately negative, equal to the value of the negative power supply. When the sine wave returns back to zero after completing the first alternation, the output also returns to zero. Since the second input alternation is negative, the output goes immediately positive, remaining there until the input sine wave returns to zero. It is obvious that the sine wave is altered in this amplifier, since the output is a square wave. If a sine wave is required at output, the stage gain must be reduced. This is accomplished by providing feedback to the input and is called a closed-loop arrangement.

- Closed-loop operation.

To assure that input is duplicated in shape at output, the output signal is reduced in amplitude and fed back to input. Feedback determines "op" amp gain. Much signal feedback to input reduces gain; whereas, little signal feedback increases gain. Too much signal feedback creates distortion (change in shape) in input and output signal.

The closed-loop operation can be accomplished in two ways: the inverting and noninverting configuration. When inverting mode is used, the signal at the input will be phase inverted (180°) in output. Of course, noninverting provides a nonshifted input at output signal. In either case, output signal amplitude is controlled by the amount of feedback allowed.

Figure 8 shows the inverting configuration. Figure 9 describes noninverting configuration. The inverting mode is the most popular of the two and is practical.

Figure 8 shows feedback placed on the top input, called the inverting input. Resistors R_1 and R_2 are chosen to provide voltage division for the amount of signal voltage feedback required for the particular application. Changing the values of R_1 and R_2 changes the amount of feedback required. The ratio of R_1/R_2 determines feedback voltage. If $R_1 = R_2$, the gain of the amplifier will be zero. Input and output amplitudes will be the same. Increasing the resistance of R_1 (compared to R_2) will increase gain, because less voltage is fed back.

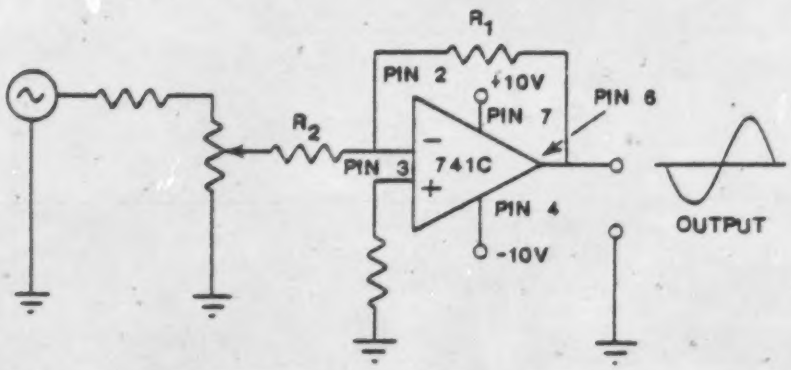


Figure 8. Inverting Mode with Feedback.

Output signal will be 180° out of phase with the input signal for the inverting mode shown in Figure 8.

Figure 9 shows the input signal applied to the noninverting input, with feedback fed to the inverting

input. This mode provides a noninverted output signal with its amplitude controlled by the feedback on Pin 2. (Notice the input and output signals.)

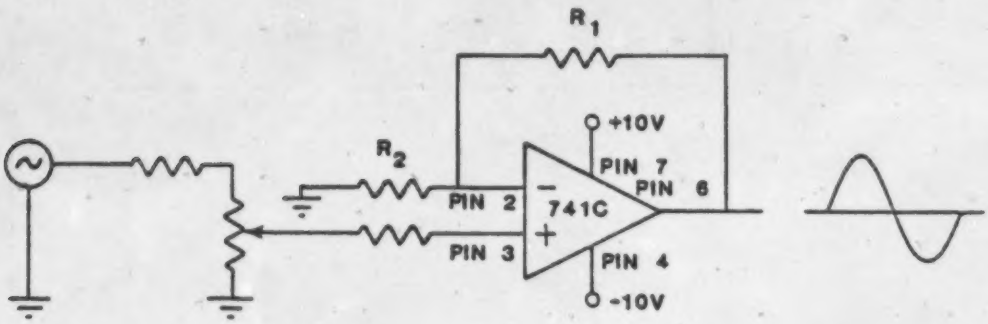


Figure 9. Noninverting Mode with Feedback.

The gain of either the inverting or noninverting amplifiers can be calculated. The proper calculations are shown here with the inverting mode shown first.

$$\text{gain} = \frac{R_1}{R_2} \qquad \text{inverting}$$

$$\text{gain} = \frac{R_1}{R_2} + 1 \qquad \text{noninverting}$$

An example of each calculation may provide further understanding.

EXAMPLES OF CALCULATIONS:

Inverting

R_1 = 10 KΩ

R_2 = 1 KΩ

Input signal = 0.1 V

Calculation

$$\text{Stage gain} = \frac{R_1}{R_2} \quad \frac{10\ K\Omega}{1\ K\Omega} = 10$$

Input	Output
0.1 V x 10	= 1 V

Noninverting

R_1 = 10 KΩ

R_2 = 1 KΩ

Input = 0.1 V

Calculation

$$\frac{R_1}{R_2} + 1 \quad \frac{10\ K\Omega}{1\ K\Omega} = 11$$

Input	Output
0.1 V x 11	= 1Ì V

Frequency response can also be calculated for an "op" amp. This is the range of frequencies that can be passed by the amplifier. The formula is as follows:

$$\text{bandwidth} = \frac{\text{gain - bandwidth product}}{\text{gain}}$$

EXAMPLE OF CALCULATION:

Say the gain-bandwidth product is 1 MHz. Using the gain for the previous calculation shown for an inverting amplifier, it is the following:

Calculation

$$\text{bandwidth} = \frac{\text{gain - bandwidth product}}{\text{gain}}$$

$$= \frac{1 \text{ MHz}}{10}$$

$$= 100{,}000 \text{ Hz}$$

The same calculation works for the noninverting amplifier as long as the proper gain is selected from the gain calculation done on the preceding pages.

PRACTICAL OPERATIONAL AMPLIFIER USES

"Op" amps are a most useful IC. An "op" amp can replace many of the discrete component uses and often does a better job. Several uses are active filters, summing adders, and difference amplifiers.

- Active filters.

(If a review of filters is necessary, return to appropriate materials.) Because of the fast rate at which an "op" amp can change, it is an ideal device for frequency filters. An "op" amp classed as an active device can be used to amplify a changing input signal in accommodating a wide range of frequencies. The filter portion must exist in discrete components outside the chip. However, because the "op" amp can react to the drop in amplitude as the filter pass response falls off, the chip makes the fall-off quicker and sharper. Figure 10 illustrates three different graphs for low pass, high pass, and band pass filters, respectively (in A, B, and C) showing the rapid fall-off response.

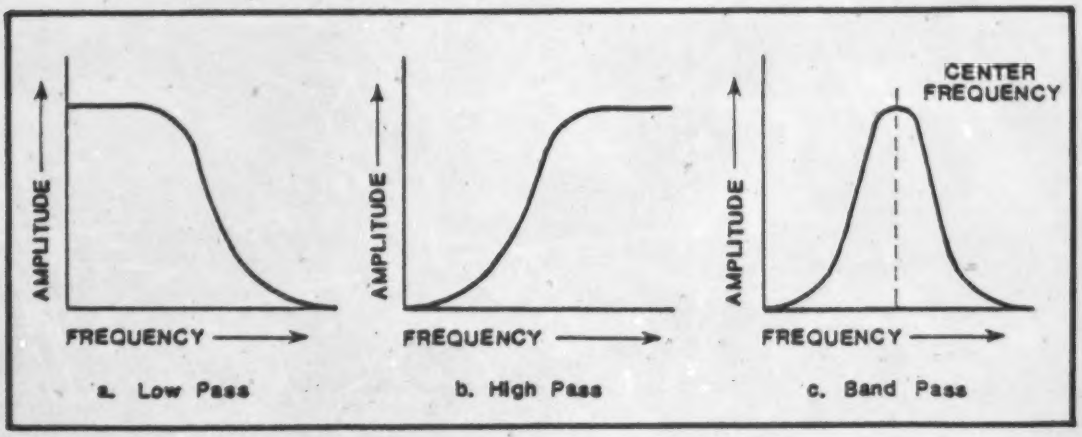


Figure 10. Low Pass, High Pass, and Band Pass Filters with Fall-Off Response.

"Op" amp circuits used to perform these filter circuits in Figure 10 are shown in Figure 11. In low and high pass filters, the filter is placed in the input lead;

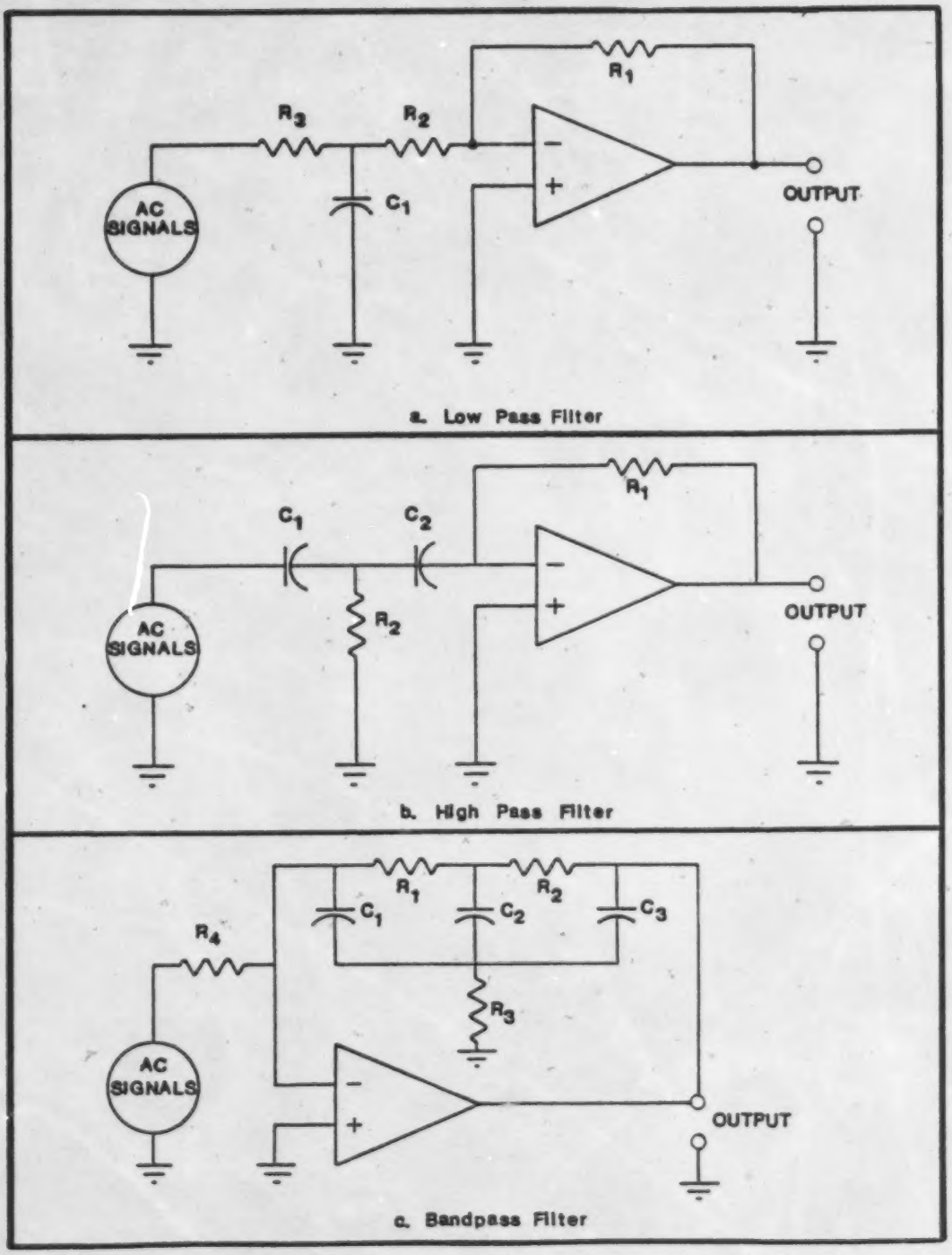


Figure 11. "Op" Amp Circuits Used to Perform Filter Circuits Shown in Figure 10.

whereas, the band pass filter is located in the feedback loop and affects the amplitude and frequency of the feedback voltage.

Considerable gain is obtained at frequencies passed to output with a high attenuation at all other frequencies, such that they are blocked from reaching the output.

- Summing Adders.

In some applications, many voltages must be added together to obtain net voltage value. These voltages can be either d.c. or a.c., and are fed to the "op" amp via input resistors. Figure 12 is one example of a summing or adder circuit.

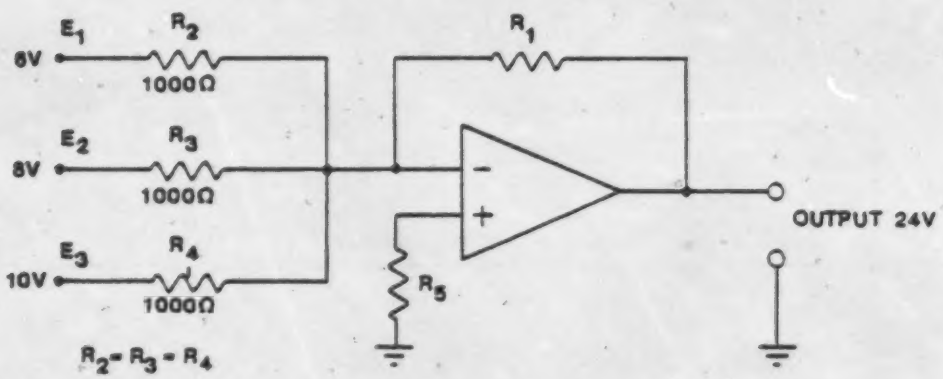


Figure 12. 3-Input Analog Adder Amplifier.

This circuit is especially useful in tallying the results of several inputs (not limited to 3). If the designer wishes one input to be weighted heavier than another, input resistors R_2, R_3, and R_4 can be ratioed to obtain the desired results. Figure 13 is an example. In this circuit, E_1 provides 6 V, whereas E_2 and E_3 provide 3 volts and 1 1/2 volts, respectively.

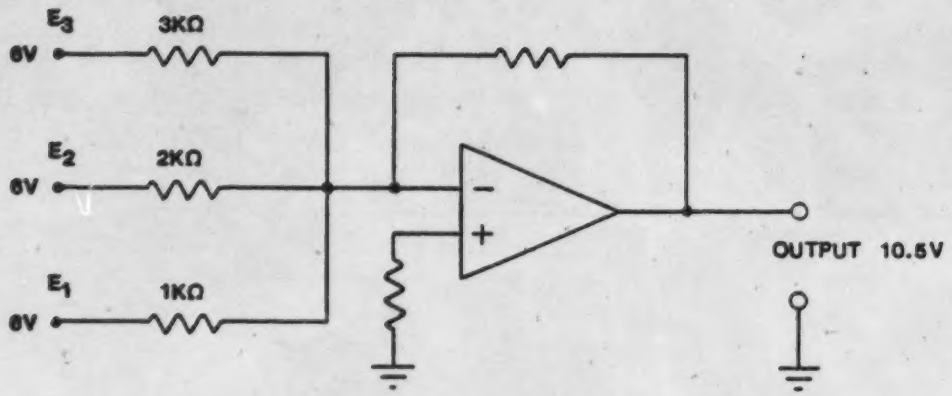


Figure 13. 3-Input Analog Scaler Adder Amplifier.

These circuits are used to convert back and forth between analog and digital signals.

• Differential amplifiers.

Some electronic applications require comparing two signals and subtracting the two for a net difference. One such case is the AFC circuit used in electronic receivers. An example of a basic difference amplifier is shown in Figure 14.

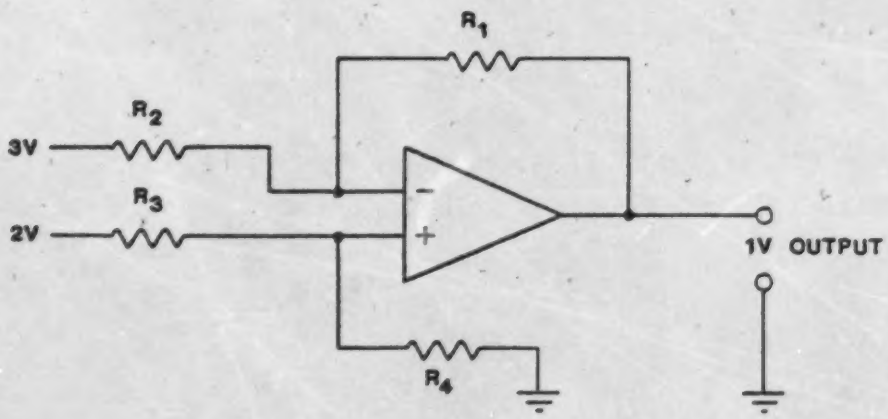


Figure 14. Difference Amplifier.

In this application, only two voltages can be compared. If more voltages are to be compared, input must have either a summer or subtractor circuit preceding R_2 and R_3. Any number of uses is possible according to the desired design. Figure 15 shows an example of a summer circuit preceding the difference inputs.

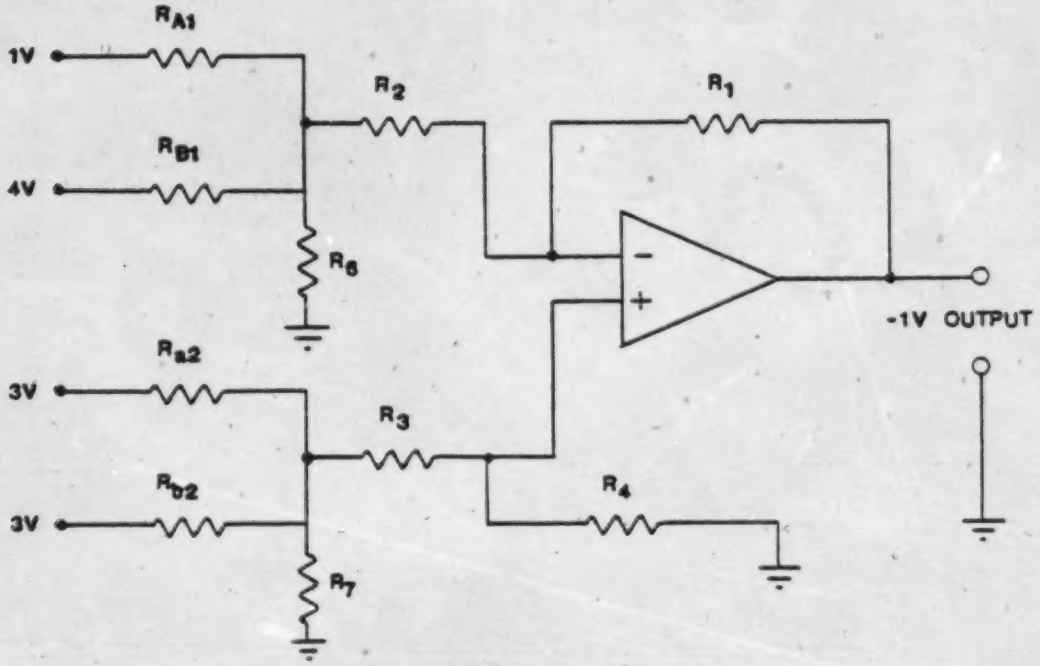


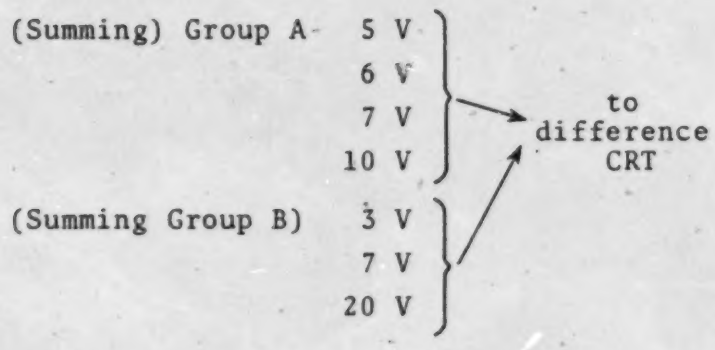
Figure 15. Difference Amp with Adder Input.

This circuit, like others, can be arranged to fit any requirement. In Figures 14 and 15, R_1 and R_2 with R_3 and R_4 are difference inputs, with R_{a_1} and R_{b_1} and R_{a_2} and R_{b_2} serving as the adder portion of the circuit.

Although only surface theory and practical level have been discussed, this material provides awareness of circuits in use. Later modules will show uses in a system application.

EXERCISES

1. State a probable reason for integrated circuits remaining in the field of electronics.
2. Give two advantages tubes have over IC's.
3. State the major advantages IC's present to energy conservation.
4. Draw a circuit that provides the difference between the following groups at output. Use an "op" amp as the main device.



LABORATORY MATERIALS

1 triggered 10 MHz oscilloscope (dual trace if possible).
1 d.c.-a.c. ohms multimeter with leads.
1 positive 10-volt d.c. power supply.
1 negative 10-volt d.c. power supply.
1 sine-wave generator (audio).
1 breadboard.
Connecting wire.
1 741C operational amplifier.

2 10-KΩ 1/2 watt 5% resistors.
2 1-KΩ 1/2 watt 5% resistors.
1 1-KΩ 1/2 watt potentiometer.
1 10-μFd capacitor 25 WV d.c. (electrolytic).
2 0022-μFd capacitor 25 WV d.c. (non-electrolytic).

LABORATORY PROCEDURES

LABORATORY 1. COMPARATOR.

This lab gives a practical look at the "op" amp explained in this module. Equipment and parts required can be found in most inventories.

PROCEDURE

1. Construct the circuit (shown in Figure 16 below) for a comparator.

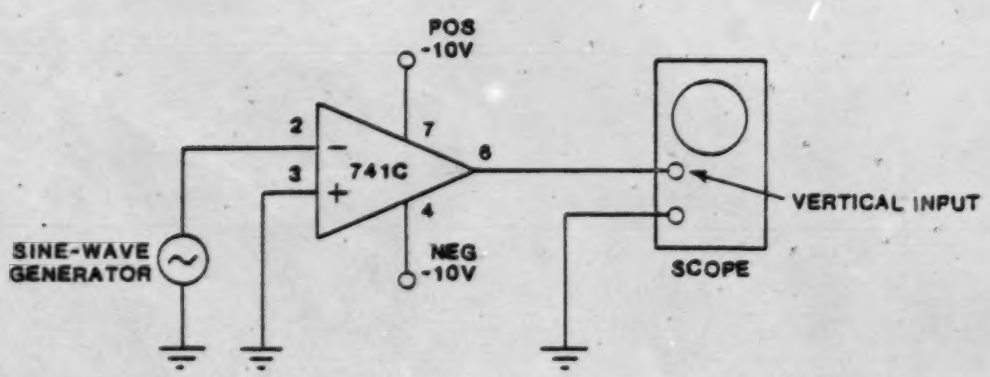


Figure 16. Comparator.

2. Set the sine-wave generator for 1 KHz (frequency). With the oscilloscope showing a trace, adjust the sine-wave generator amplitude control so an acceptable trace (square wave) is visible on the screen. Increase the generator output only enough to provide a good amplitude on the scope for viewing.
3. In the graph in Data Table 1, draw the input and output waveform (two cycles for both), noting that the input is a sine wave; whereas, the output is a square wave. Notice that the output is distorted or changed compared to the input, a characteristic of the comparator.

LABORATORY 2. INVERTING AMPLIFIER (WITH FEEDBACK).

PROCEDURE

1. Construct the circuit (shown in Figure 17) for an inverting amplifier.

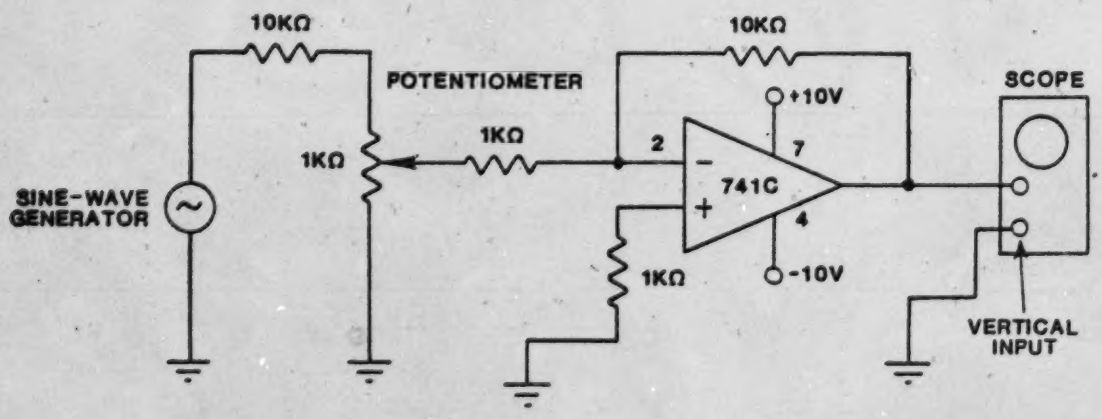


Figure 17. Inverting Amplifier.

2. Adjust sine-wave generator to 1 KHz.
3. Adjust the potentiometer so there is 0.3 volts Peak-Peak at Pin 2 of the "op" amp (use the oscilloscope-vertical input connected to Pin 2 and the oscilloscope ground to the circuit ground).
4. With the oscilloscopes attached to Pin 6 (vertical input of scope to Pin 6), measure the P-P a.c. waveform. (Scope ground must be connected to circuit ground.)
5. Adjust the potentiometer for the following input voltage steps and measure at Pin 6 with the scope.
   a. 1 V.
   b. 3 V.
   c. 5 V.
   d. 7 V.
   e. 9 V.
6. In Data Table 2, plot the input and output voltages for the input voltages shown in Step 5. (A dual trace scope works best, in that input and output can be seen at the same time.)

LABORATORY 3. NONINVERTING AMPLIFIER.

PROCEDURE

1. Construct the circuit for the noninverting amplifier shown in Figure 18.
2. Adjust the sine-wave generator frequency for 1 KHz and an output of 0.2 volts. (Use the oscilloscope to measure Pin 3 voltage for 0.2 volts. Scope vertical input to Pin 3; scope ground to circuit ground.)

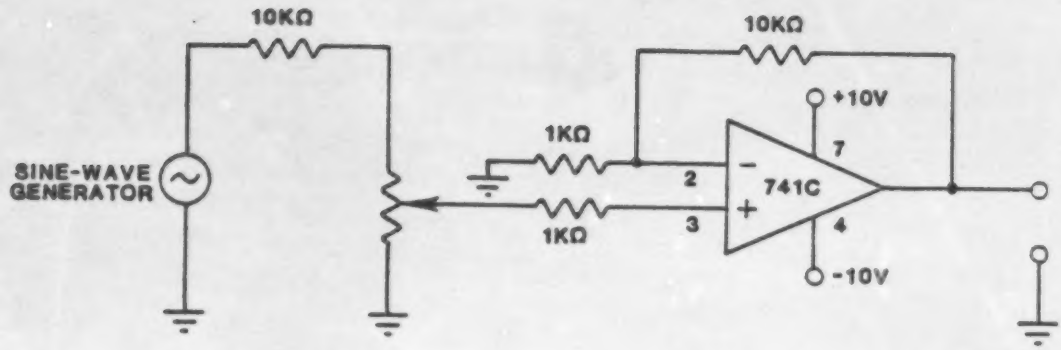


Figure 18. Noninverting Amplifier.

3. With the oscilloscope, measure the P-P voltage at the output Pin 6. (Scope vertical input to Pin 6; scope ground to circuit ground.)
4. Adjust the potentiometer for the following input voltage steps and measure at Pins 2 and 6 with the scope. Plot input and output waves in Data Table 3. (A dual trace scope works best, in that input and output can be seen at the same time.)
   a. 1 V.
   b. 3 V.
   c. 5 V.
   d. 7 V.
   e. 9 V.

LABORATORY 4. LOW PASS FILTER.

PROCEDURE

1. Construct the circuit shown in Figure 19.

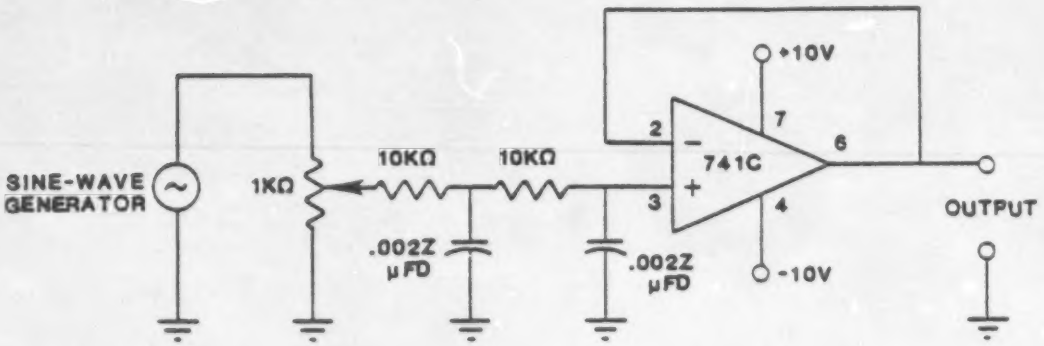


Figure 19. Noninverting Low Pass Filter.

2. Set the sine-wave generator to 1 KHz. Set the sine-wave generator output level and the 1 KΩ potentiometer so Pin 6 is precisely 4.0 V P-P on the oscilloscope. Plot this P-P value on the left-hand side of the graph in Data Table 4 (Step 1).
3. Adjust the sine-wave generator to 1.5 KHz through 25 KHz in 0.5 KHz increments and plot each output measured (Pin 6) on the graph. Example:

   1.5 KHz – Plot above Step 2
   2.0 KHz – Plot above Step 3
   20 KHz – Plot above Step 11

   } Reference Data Table 4.

   (Notice the reduced P-P value for each frequency as frequency rises.)

LABORATORY 5. HIGH PASS FILTER.

PROCEDURE

1. Construct the circuit in Figure 20.

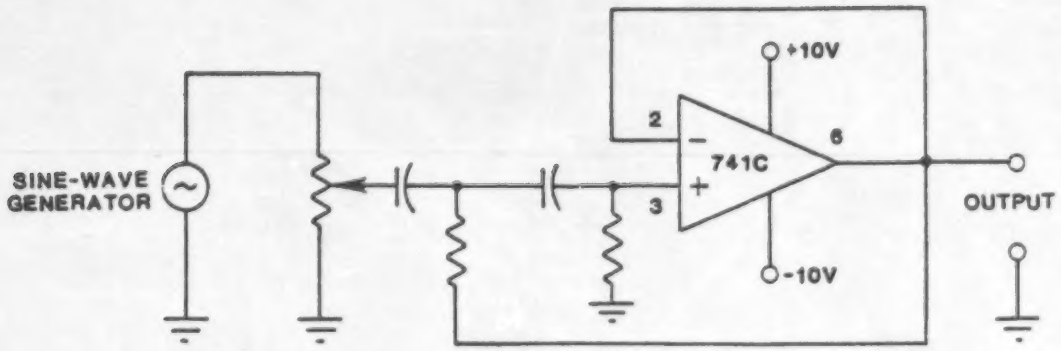
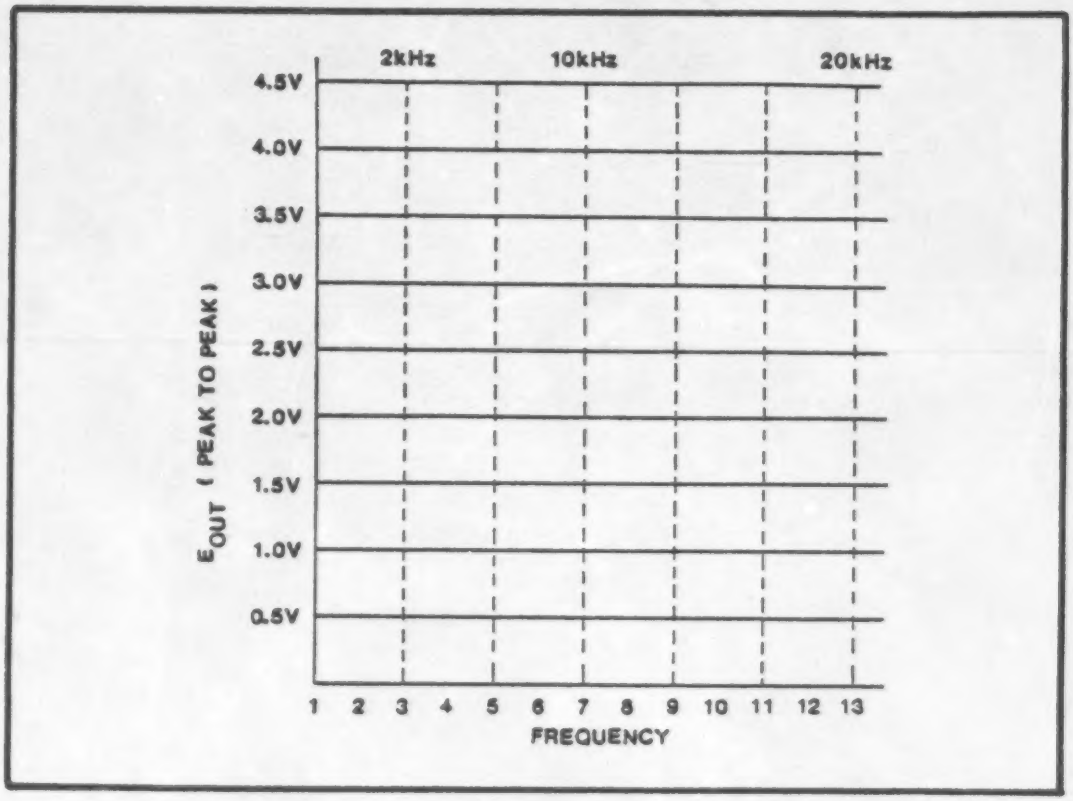


Figure 20. Circuit.

2. Set the sine-wave generator to 25 KHz and the output voltage of the generator to precisely 4.0 volts P-P (measured at Pin 6 with the oscilloscope).
3. Plot this 4.0 voltage value on the right edge of the graph in Data Table 5.
4. Change the frequency of the generator (not the output voltage level) in 0.5 KHz increments and plot each from right to left on the graph in Data Table 5. Notice that as frequency decreases, the voltage at Pin 6 also decreases.

DATA TABLES

DATA TABLE 1. COMPARATOR.



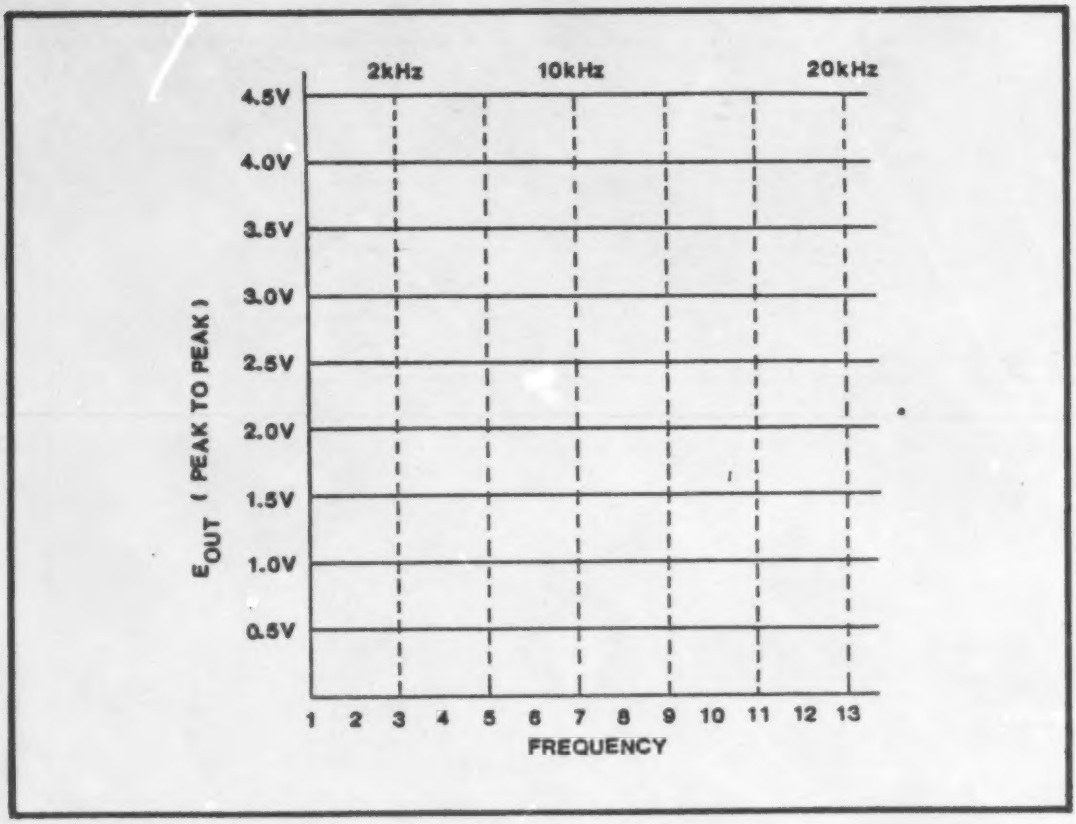
DATA TABLE 2. INVERTING AMPLIFIER (WITH FEEDBACK).

	Input Pin 2 voltage (P-P)	Output Pin 6 voltage (P-P)
1 V		
3 V		
5 V		
7 V		
9 V		

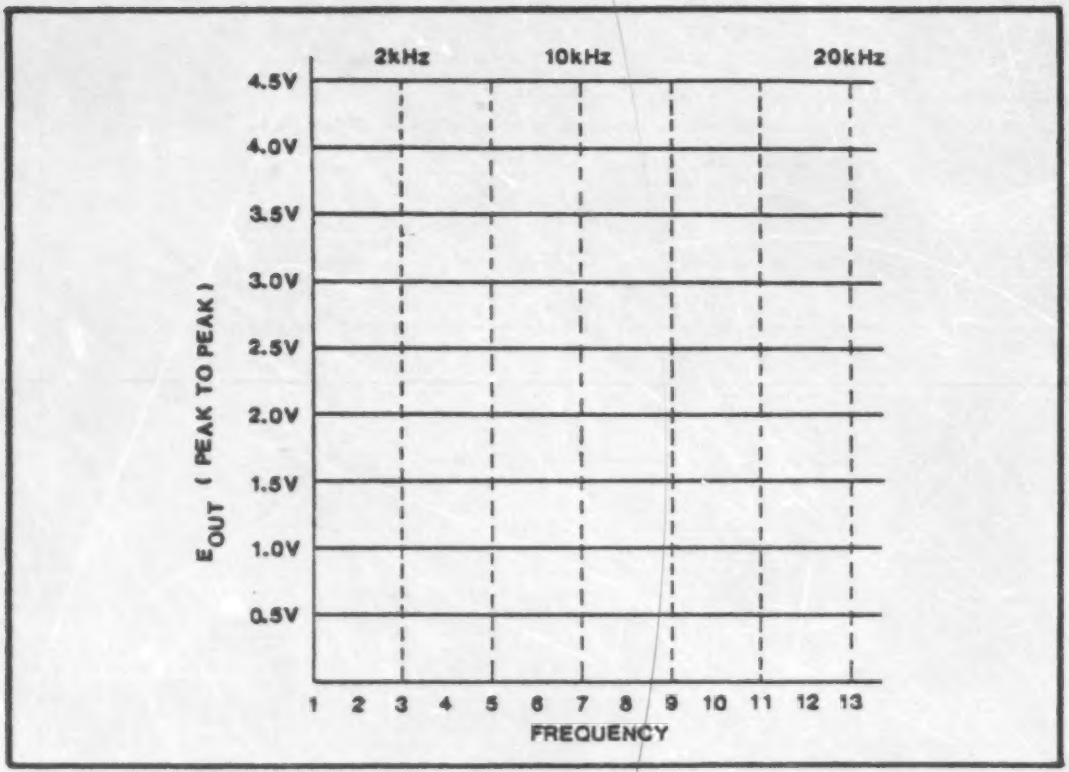
DATA TABLE 3. NONINVERTING AMPLIFIER.

	Input Pin 3 voltage (P-P)	Output Pin 6 voltage (P-P)
1 V		
3 V		
5 V		
7 V		
9 V		

DATA TABLE 4. LOW PASS FILTER.



DATA TABLE 5. HIGH PASS FILTER.



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Heathkit Learning Publications.. Semiconductor Devices. 1st ed. Benton Harbor, MI: Heath Company, 1978.

Maloney, Timothy J. Industrial Solid-State Electronics Devices and Systems. Englewood Cliffs, NJ: Prentice Hall, 1979.

1. Which of the following is not an advantage of IC's as compared to discrete devices?
   a. Low operating voltages.
   b. Small in size.
   c. Sensitive to heat.
   d. Low voltage operation.
2. An advantage of the differential amplifier is that...
   a. it is easy to remove components in it.
   b. it has common-mode rejection ability.
   c. it can amplify d.c. signals.
   d. it can amplify a.c. signals.
3. Which of the circuits listed uses no feedback?
   a. Low pass filter ("op" amp).
   b. High pass filter ("op" amp).
   c. Comparator ("op" amp).
   d. Inverted input ("op" amp).
4. Refer to Figure 21. What is the voltage at the inverted input (-terminal)?
   a. +5 V.
   b. -10 V.
   c. 0 V.
   d. -5 V.
   e. None of the above.
5. What kind of amplifier is shown in Figure 21?
   a. Comparator.
   b. Summing "op" amp.
   c. Inverted input "op" amp.
   d. Noninverted input "op" amp.

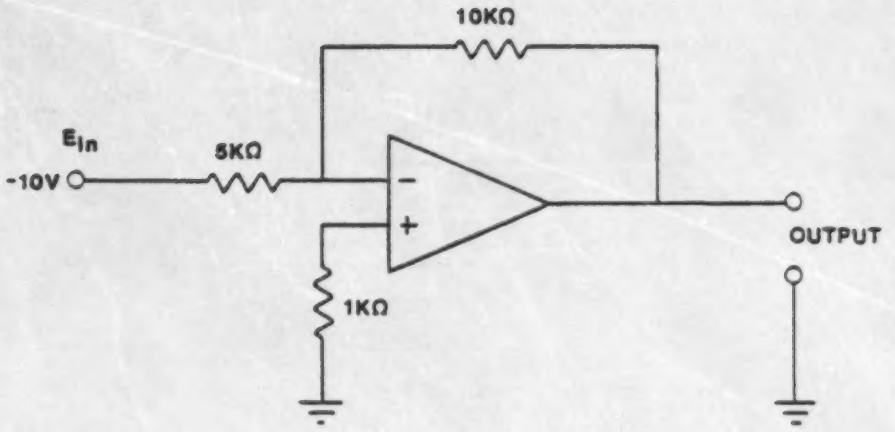


Figure 21. Figure for Questions 4 and 5.

6. In what sequence are the three sections of an "op" amp (differential amplifier, output amplifier, voltage amplifier)?

7. Where the power output requirement is above 1 watt, "op" amps must be used.
   a. True.
   b. False.

8. Which of the following practical circuits can be used to reproduce a signal without distortion?
   a. Comparator.
   b. Summing.
   c. Differential.
   d. Inverted input "op" amp.
   e. Noninverted input "op" amp.

9. Which of the following inverts the output compared to the input?
   a. Comparator "op" amp.
   b. Inverted input "op" amp.
   c. Noninverted input "op" amp.
   d. Differential "op" amp.

10. In Figure 22, which statements (below) are correct?
   a. When E_{inv} and E_{noninv} = 5 volts, each E_o = 0 volts.
   b. If the input E_{inv} is a sine wave, E_o is a sine wave.
   c. When E_{inv} is more positive than E_{noninv}, E_o is positive.

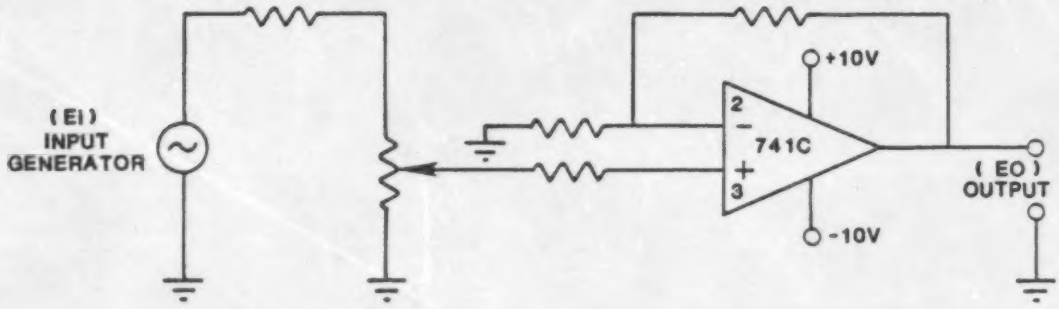
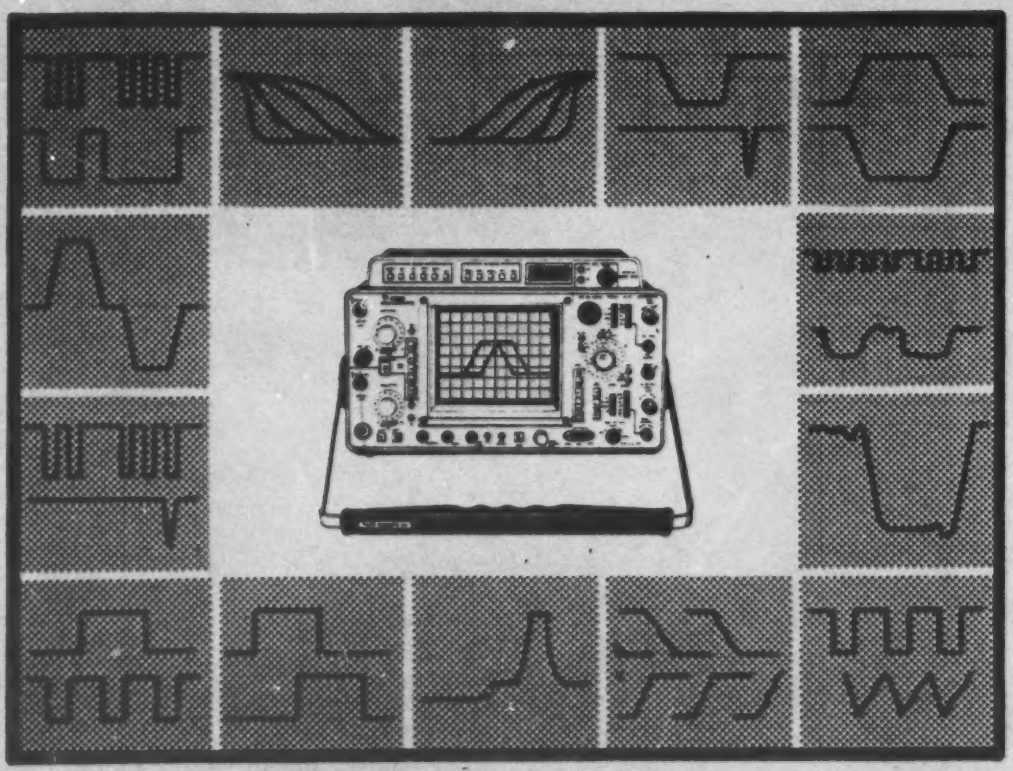


Figure 22. Operational Amplifier.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-05

INDICATORS AND DISPLAYS

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INTRODUCTION

Indicators and displays are used universally to give people information. Indicators and displays are incorporated in electronic equipment to give information about conditions within a system or stage. While not all of these devices are mounted externally, most are visible to persons using the equipment. Some indicators must be viewed frequently; others may be viewed only occasionally. Indicators can provide only two pieces of information: ON or OFF. Displays can provide more information.

This module covers incandescent and neon lamps and several light-emitting devices that are currently available. The last part of the module covers a special device called an optical coupler, which incorporates light-emitting diodes (LEDs) used to transmit information from one stage to another and provides electrical isolation.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Name three factors by which incandescent lamps are rated.
2. Describe how a neon lamp operates and indicate why resistors are wired in series with these devices.

3. Describe the operation of both single and clustered LEDs and draw the accompanying circuit component.
4. State the difference between reflective and transmissive LCDs.
5. Describe the circuit of an optical coupler and state the advantages of this coupling method over eariler approaches used for interfacing.

INCANDESCENT LAMPS

Lamps are used to provide indication of a condition of the equipment to which they are attached. Lamps are two-state devices (ON or OFF), and they represent only two conditions. It is rare to find lamps used to provide more than two states; however, it is not impossible. Light levels can be differentiated under certain conditions, but it is difficult for the unaided human eye to distinguish light level differences.

The above discussion about lamps assumes an indicator application. While lamps may also be used to provide light illumination, this is not the purpose in electronic applications. However, since heat is a byproduct, lamps are sometimes used as a constant or changing heat source. This module will discuss lamps when used as indicators.

Incandescent lamps are usually rated by amperes, voltage, and wattage. This information is important when choosing a proper lamp.

A lamp has three elements: a filament, a base, and a glass cover. Depending upon the materials used to construct the light producing filament, the lamp may withstand a predetermined current value. The amount of current flowing is dependent upon the voltage applied to, and the resistance of, the lamp.

Lamps are produced with specific uses in mind; for example, a 6-volt lamp is normally operated at 6 volts. Resistance constructed into the filament provides opposition to current flow as it is moved by the power source. When these conditions are met, the lamp provides a pre-intended brilliance. Applying less or more voltage causes brightness to

decrease or increase. As the filament heats or cools, its resistance changes. Therefore, the rated voltage and current values provide a given brilliance only when the lamp is operated as suggested by the manufacturer. Higher voltages cause more current to flow, thus reducing lamp life.

Lamps are also identified by their connecting base. Base type is determined by physical requirements and size limitations, as well as vibration parameters. Base types include the threaded base, the twist lock base, the snap-in base, and the wire lead base. The most common bases are the threaded and the twist lock styles. Figure 1 shows examples of each. Figures 1a, 1b, and 1c all require lamp sockets or holders, whereas, Figure 1d solders into the circuit.

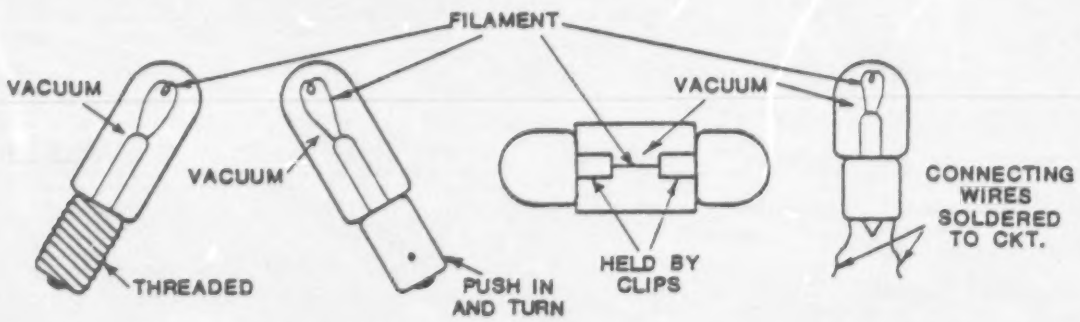


Figure 1. Lamp Styles.

Bulb ratings are not always stamped on the device. A manufacturer's identification number is usually provided somewhere on either the glass or metal part of the lamp. To determine the lamp ratings, manufacture data must be referenced.

While vibration is not usually a major case of premature failure, frequently turning the lamp on and off is. If an application requires continued, or frequent ON-OFF states, neon or LED lamps are suggested. Of course, voltage and current requirements must be met whichever lamp is used.

NEON LAMPS

Rather than a filament, a neon lamp has two electrodes placed parallel inside the lamp. During manufacturing, the vacuum inside the glass is filled with neon gas. When a sufficient difference is applied to its electrodes, the neon gas ionizes and glows. Figure 2 shows the structure of the neon device.

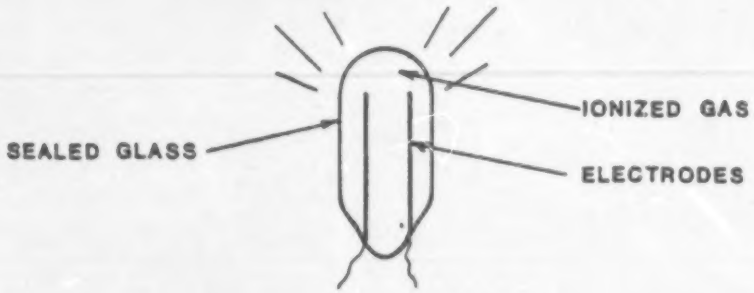


Figure 2. Structure of the Neon Device.

All neon lamps have a voltage at which they will ionize. Design dictates what the voltage will be for ionizing. Figure 3 shows the firing and cutting off relationships for this device.

Notice that it takes a higher voltage to fire the lamp than to turn it off. Gas has a tendency to remain ionized until voltage is reduced sufficiently to turn it off.

It is impossible to remove all oxygen from the glass enclosure when the neon is manufactured. When the neon gas ionizes, it burns at a very slow rate. However, eventual failure is inevitable. This further advocates operating the neon with only enough voltage to cause it to fire. Higher voltage increases brilliance – but also produces hotter burning. While a neon lamp produces a brighter light with higher voltage, it is not recommended – even for a short period of time.

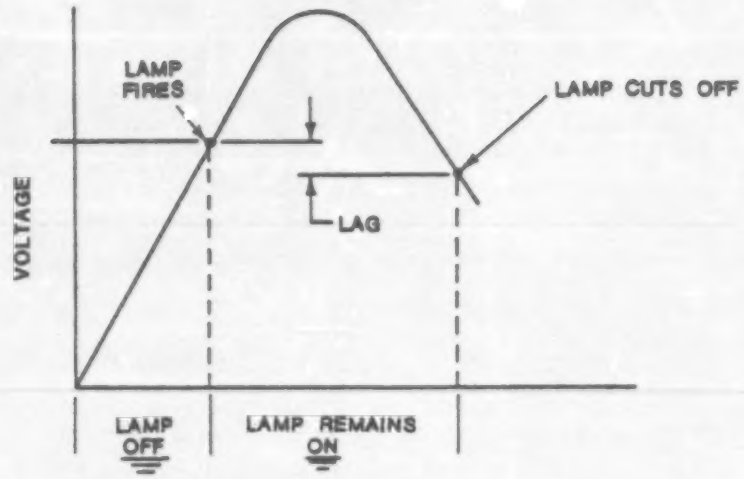


Figure 3. ON-OFF Characteristics.

Because the firing voltage is low, most neons are connected in a series with a resistor. The resistor allows only the proper voltage to be applied to the lamp. Without this resistor, immediate permanent damage may occur. Therefore, each lamp used should comply with this requirement.

Most neon lamps are stamped with a manufacturer's part number. If the firing voltage must be known, manufacturer's data must be referenced to determine this value.

LIGHT-EMITTING DIODES (LEDs)

LEDs are small, inexpensive, low-voltage lamps with a long operating life. Recent technology has made use of this device in the digital and computer world. LEDs firing voltage is typically lower than that of neon lamps. Light output is about the same.

While incandescent and neon lamps can vary in light output, neither is acceptable in the digital computer, because response time to changing input voltages is slow.

However, with the development of the solid-state durable LED, the problem was solved. LEDs respond so fast they can be used to transfer rapidly-changing information to a receiving device with little or no distortion.

The light-emitting diode is, like solid-state diodes, a P-N junction diode. When a forward bias voltage of the right value is applied, holes are forced to combine with available electrons. This combining action produces energy called a photon. The human eye detects the light energy product produced as a result of recombining.

Different colors of light may be produced. However, once a diode is manufactured, the device will have only one color. Thus if red is required, a red LED must be purchased. Green and yellow LEDs are also available. The color is determined by the material used to manufacture it. Figure 4 shows the structure of a LED.

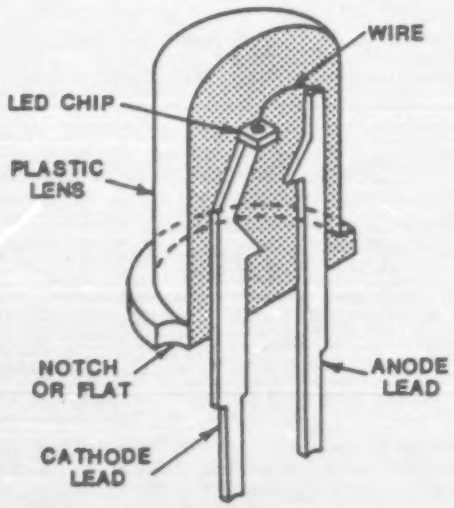


Figure 4. LED Construction.

While these devices have many advantages, they can be damaged permanently by applying too much voltage or current. Most operate between 1.2 volts and 1.6 volts. Once the device conducts, the resistance of the junction remains essentially constant and very low. However, the forward current increases as

applied voltage is increased. Figure 5 shows the relationship between voltage and current of the LED. Figure 5 shows how current flow through the device changes with a small variation in forward voltage.

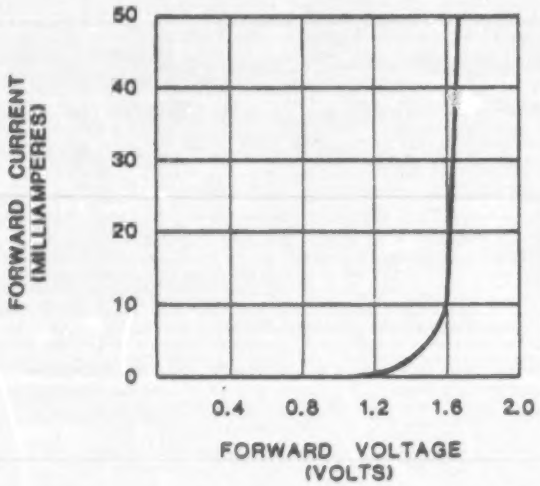


Figure 5. Voltage-Current Relationship.

If a changing brightness is required, input voltage is varied. The forward current is changed from zero milliamperes to about 50 milliamperes. This current change causes a linear change in output brightness (if measured with a light-sensitive meter, not the human eye). Figure 6 shows the output from a changing current.

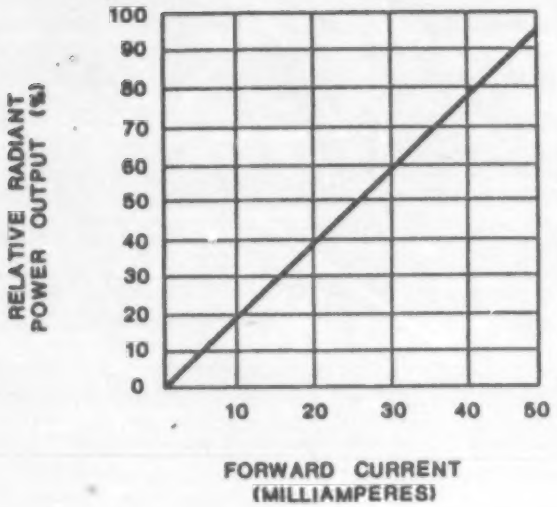


Figure 6. Light Output Versus Forward Current.

LED USES

LEDs can be used as indicators or transmitting devices. Almost all uses require placing a resistor in a series with the LED. This is because the forward operating current must be limited to a safe value in order to prevent damage. Figure 7 shows how this done.

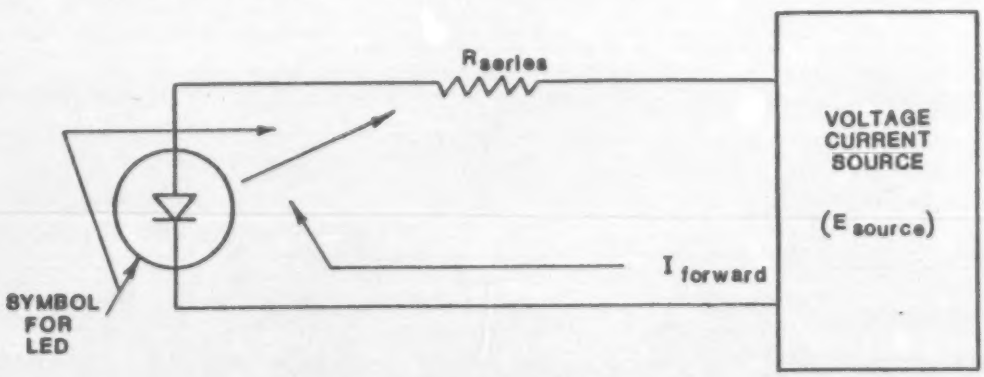


Figure 7. LED Circuit.

The value of R_{series} can be determined by the following formula:

$$R_{series} = \frac{E_{source} - 1.6}{I_{forward(max)}}$$

$$R_{series} = \frac{5\ V - 1.6}{0.050} = 68\ ohms$$

LEDs may be used individually as an ON-OFF device or as segmented display.

ON-OFF LED

One example of an ON-OFF LED is a flashing trouble indicator. In this case, the output light is a prefixed ON-OFF condition flashing at a preset rate. While the light output is not considered bright, there is sufficient output so that the device can be used in a dimly lit environment.

SEGMENT DISPLAY LEDs

Multiple single LEDs may be combined to form specific shapes such as numbers or letters. Figure 8 shows an example of a segment display capable of displaying 0, 1, 2, 3, 4, 5, 6, 7, 8, or 9 and some letters such as capital A, C, small b and d.

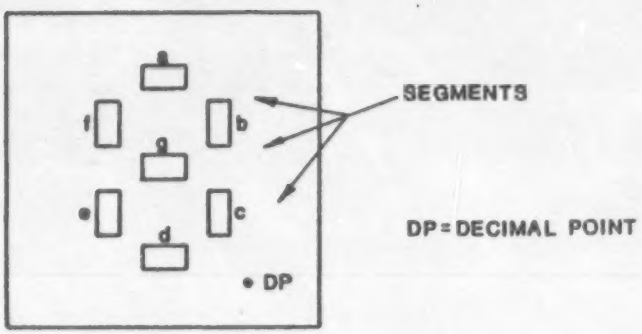


Figure 8. 0-9 Display.

Each segment may be turned ON or OFF as required to form the desired number or letter. This display has 8 LEDs with a rectangular shape, and the decimal point, which is usually round. If the letter 8, for example, is required to be lit, then all segments (with or without the decimal point) would be lit.

Electrically, there are two types of 7-segment LED displays, as shown in Figure 9. The difference is in how the LED display is connected to the power source.

Figure 9a shows ground placed on the leads of the segments that must turn on. In number 7, a, b, and c leads must be grounded. (Refer to Figure 8 for segment position.)

Figure 9b indicates that +5 volts is applied to the proper lead to turn on a segment.

IT IS IMPORTANT TO NOTE, HOWEVER, THAT A RESISTOR MUST BE PLACED IN SERIES WITH THE LEADS FOR EITHER THE COMMON CATHODE OR COMMON ANODE DISPLAY TO LIMIT CURRENT THROUGH THE LEDs. While +5 volts was chosen, any voltage within reason could be used – providing the right value series resistor was used.

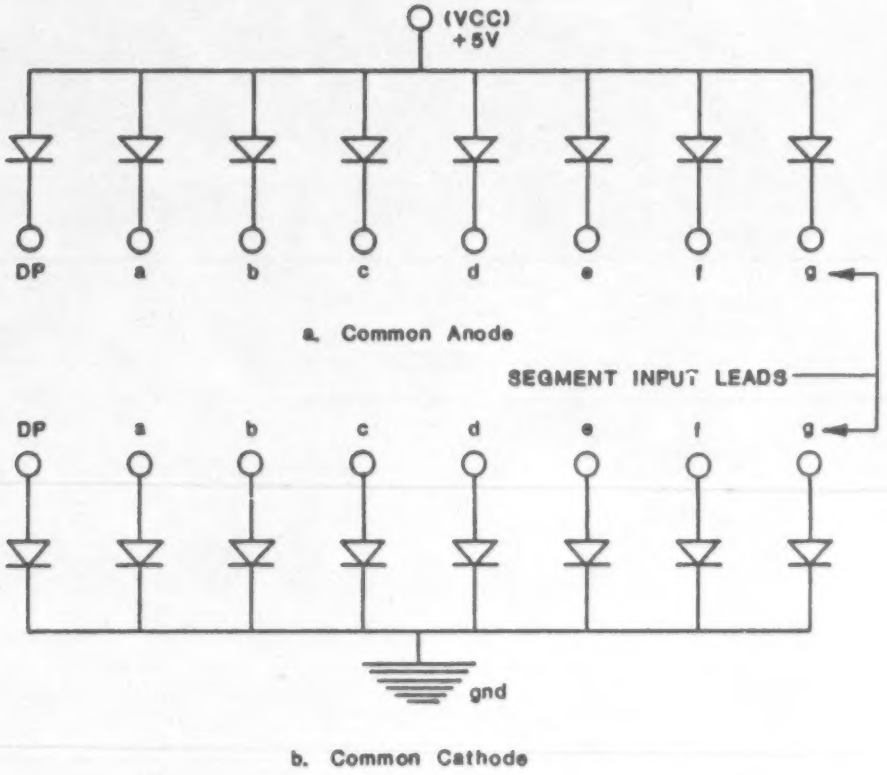


Figure 9. Two Types of 7-Segment LED Displays.

SPECIAL APPLICATION LEDs

A singular LED can be used with a light-receiving device, such as a phototransistor, to create an optical coupler. When one ON-OFF circuit must be electrically isolated from another, this approach satisfies the requirement – while still providing a transmission of the ON-OFF stated from one stage to the next. Figure 10 shows the optical coupler. The transmitting circuit is on the left; the receiving circuit is on the right.

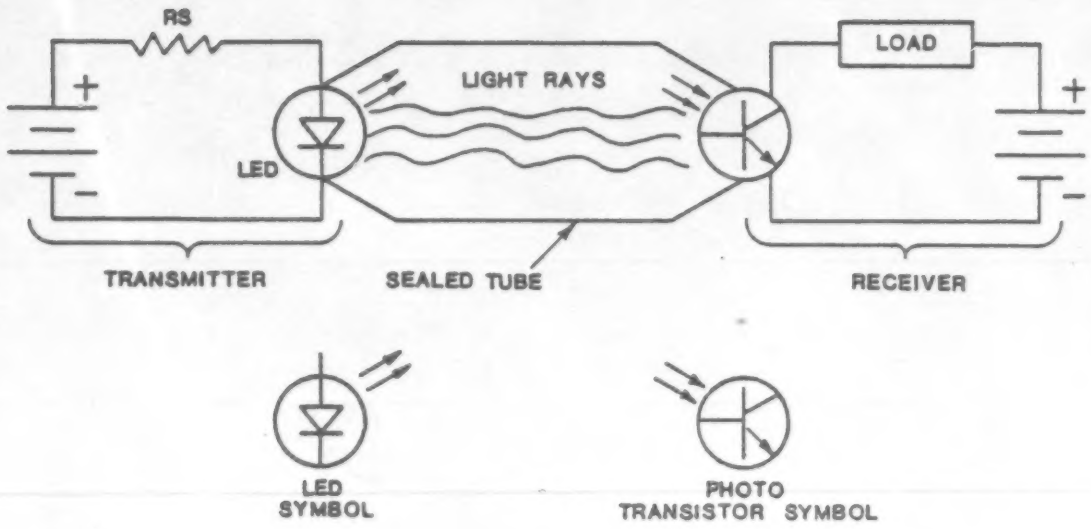


Figure 10. Optical Coupler.

Either the LED and phototransistor are physically scaled in opposite ends of a short tubular structure or they are close together so the ambient light will not interfere with the operation of the coupler.

When the LED is ON, light rays are transmitted to the phototransistor, causing the phototransistors' resistance to decrease to a low value. On the top of the phototransistor is a window allowing these light rays to reach the internal active element. Assuming the phototransistor acts as a switch, current will flow in the receiver circuit load, thus turning ON when the LED light rays shine on the phototransistor surface.

No electrical connection exists between the transmitter and receiver, yet the ON-OFF conditions are transferred. This circuit is often implemented where high voltages exist in one circuit and low voltages exist in another in order to provide isolation between the two. This circuit is also used when

electrical noise exists in a preceding circuit. However, this circuit cannot be used as a noise isolator while transferring the ON or OFF condition.

LIQUID CRYSTAL DISPLAYS (LCDs)

Much like LED displays, LCDs are designed in seven segments with a decimal point. The major advantage of LCDs as compared to LEDs is that they consume much less power, typically in the form of microwatts.

The construction of these devices is considerably different from the LEDs. LCD stands for liquid crystal display. This device is like a liquid crystal material that flows much like a liquid but also possesses the properties of a solid.

An LCD depends on an internal or external light source for viewing purposes. Most often, a reflective surface is placed behind the crystal to reflect light (reflective-type) back towards the viewer through the digit displayed (like a mirror action).

For instance, if the device is to display the digit 8 terminals, 2 through 8 would be energized, causing a frosting appearance only in those areas of 2 through 8 segments. Figure 11 describes this action.

A positive voltage would be applied to Pins 2 through 8 and the negative side to the lower oxide layer. Only those segments with voltage applied will frost. Other areas will remain clear.

LCDs operate at low voltages. Larger displays may require as much as 15-20 volts, with small watch displays as low as 1-2 volts. These devices are rugged but have operating

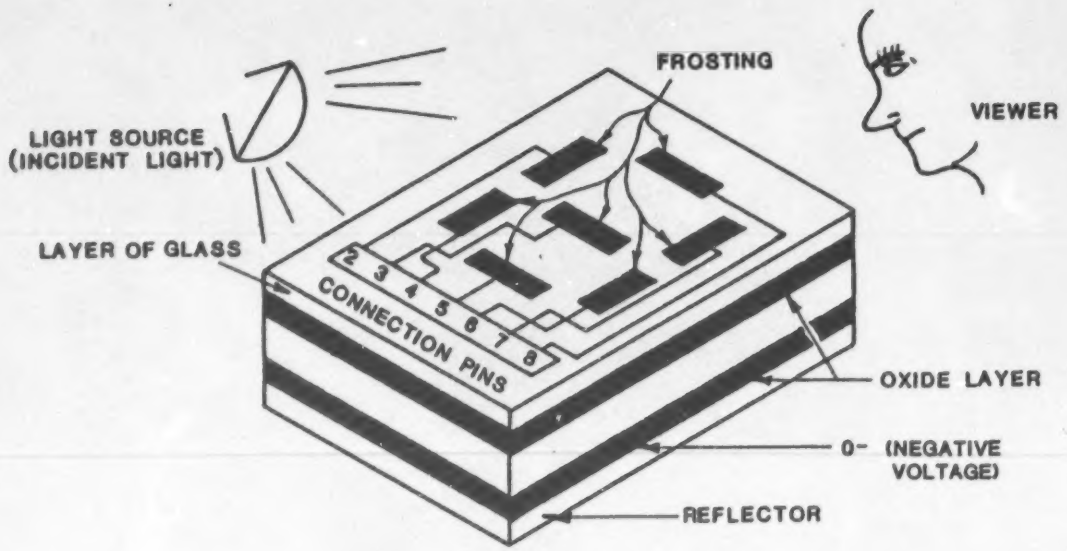


Figure 11. Reflective LCD.

temperature limitations from around 0°C to 60°C. However, the operating life is at least 15,000 hours or greater, with current requirements being much lower than LEDs.

Transmissive LCDs are also available, but will not be discussed in this module. The major difference between transmissive and previously discussed reflective LEDs is that the former has no mirror or reflective surface. The light source must be placed on the back of the device and shine through the LCD toward the viewer, as shown in Figure 12.

Greater depth of study on LED and LCD devices is beyond the scope of this course.

LEDs and LCDs are designed to produce light only. While all light sources produce heat as a by-product, these devices do not provide any significant heat. They are, therefore, useful in and around low heat applications.

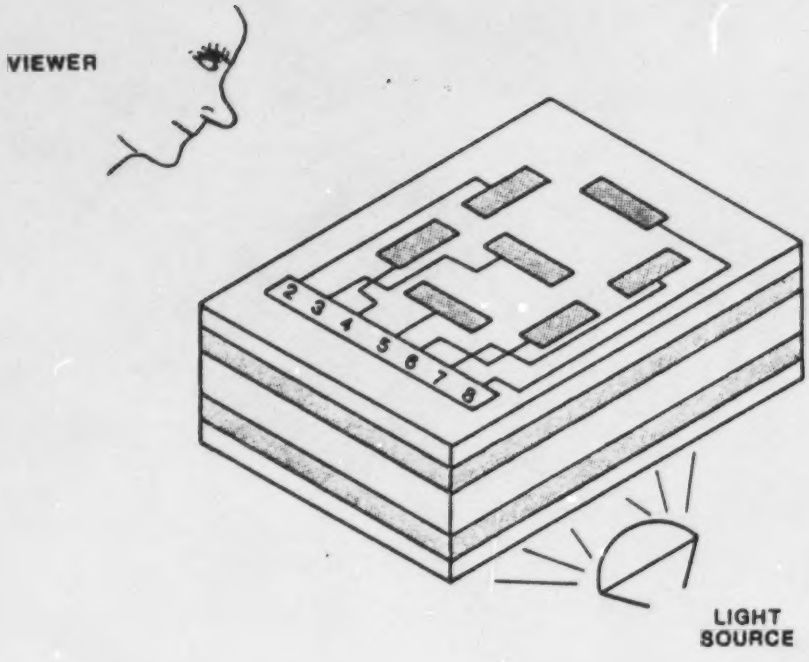


Figure 12. Light Source Placed on Back, Shining Through LCD Toward Viewer.

EXERCISES

1. State the advantages of neon lamps over incandescent lamps.
2. State the advantages of LED indicators over incandescent and neon lamps.
3. State the main disadvantage of LED indicators over incandescent lamps.
4. Describe how a LED display can be made from individual LED indicators.
5. Name the chief advantage of LCD displays over LED displays.
6. Name the chief disadvantage of LCD displays over LED displays.

LABORATORY MATERIALS

D.C. voltmeter with leads.
1 red LED.
1 1000-ohm 1/2 watt 5% resistor.
1 1000-ohm 1/2 watt potentiometer.
1 20-V d.c. power supply @ 200 mA.

LABORATORY PROCEDURES

In this experiment, the student will observe the operation of a red LED, observing current, voltage, and series resistor requirements.

1. Build the circuit shown in Figure 13, being careful to properly connect the LED cathode and anode.

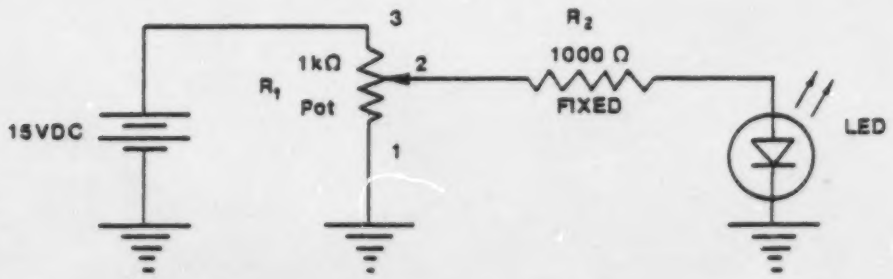


Figure 13. LED Circuit.

2. With power OFF, turn the potentiometer R_1 fully counter-clockwise.
3. Turn power supply ON and adjust so that about 15 volts is read across R_1 (from Pin 3 to Pin 1 of R_1).

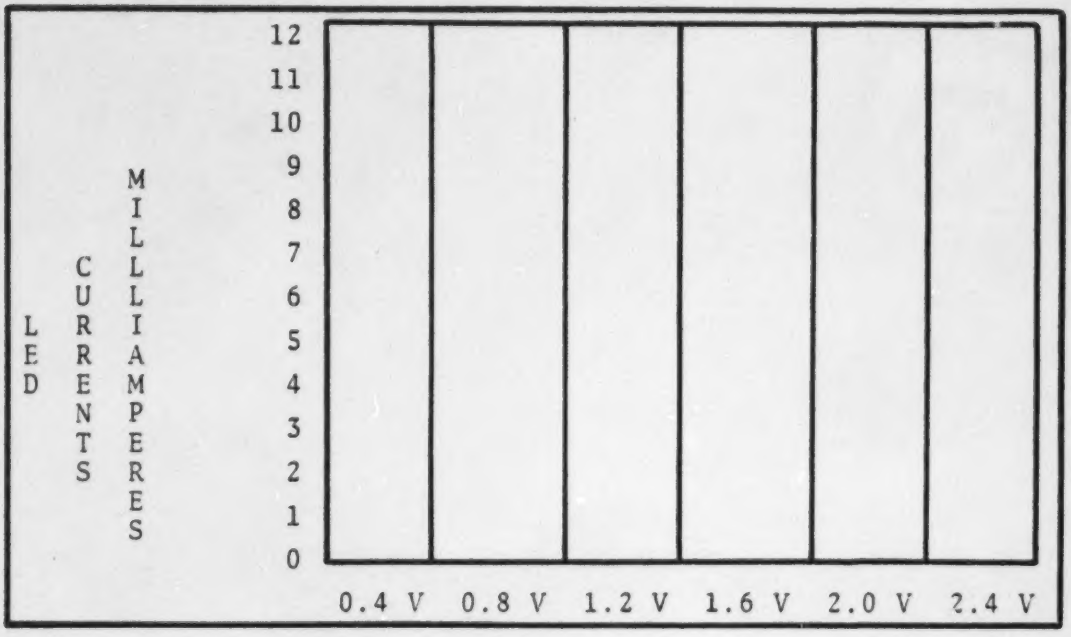
4. Adjust potentiometer slowly clockwise watching LED for brilliance. Turn potentiometer until LED lights. (Once set, do not adjust.) Measure and record voltage across LED and resistor R_2).
5. Using the proper ohms law formula, calculate the current through R_2 (measuring R_2 with an ohmmeter is advisable).
6. Adjust R_1 potentiometer to the following steps and record the current through R_2 for each step. Place the answers in Table 1. The answers for current will reflect the following steps mentioned above, as shown in Table 1 below.

TABLE 1 · LED - Current - Voltage Measurements.						
R_2 or LED Current (milliamperes)						
LED Voltage Drop	0.2 V	0.4 V	0.8 V	1.2 V	1.6 V	2.0 V

7. Plot the results of Table 1 on the graph in the Data Table.

DATA TABLE

DATA TABLE



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Maloney, Timothy J. Industrial Solid-State Electronics Devices & Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc.

TEST

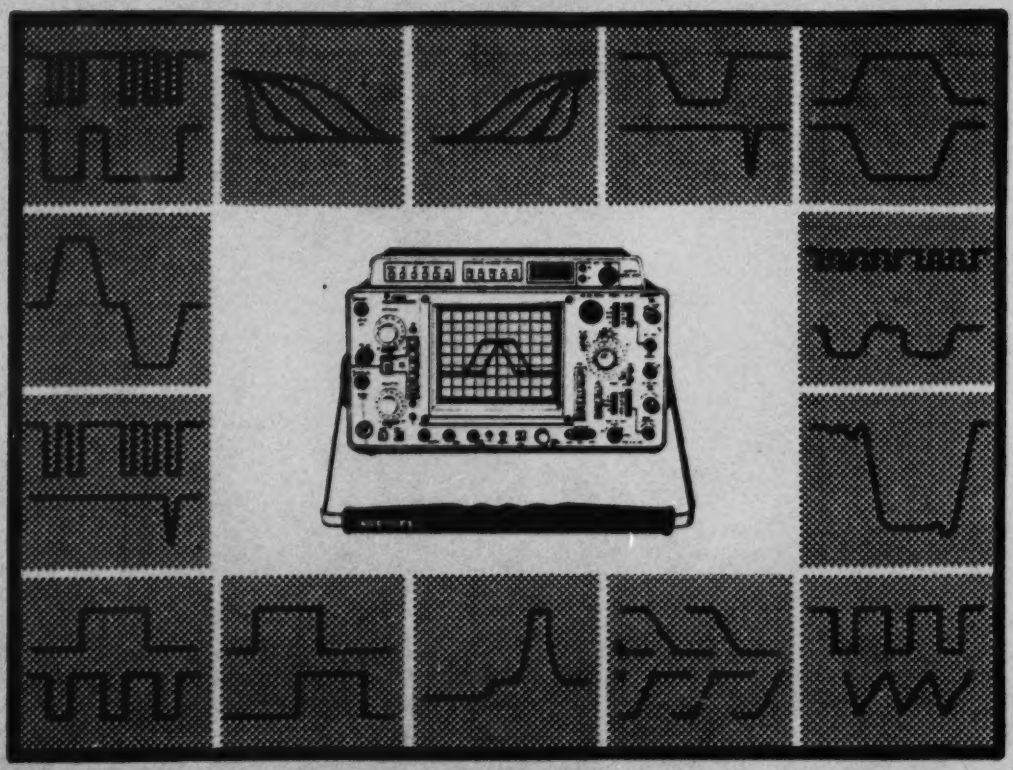
1. By what three factors are incandescent lamps rated?
   a. _____.
   b. _____.
   c. _____.
2. Resistors must be placed in series with a neon lamp to...
   a. reduce the voltage applied to the lamp.
   b. reduce the current applied to the lamp.
   c. Both a and b.
   d. Neither a or b.
3. Resistors must be placed in series with a LED indicator to...
   a. reduce the voltage applied to the lamp.
   b. reduce the current applied to the lamp.
   c. Both a and b.
   d. Neither a or b.
4. When the anode of an LED is common to all other LEDs in an LED display, the voltage applied to the cathodes must be...
   a. more positive.
   b. more negative.
   c. equal.
   d. None of the above.
5. Reflective LCDs require an internal light source.
   a. True.
   b. False.
6. Transmissive LCDs require an external light source.
   a. True.
   b. False.

7. The major drawback of LCD displays is that ...
   a. they require high voltages for operation.
   b. they are extremely fragile.
   c. they have temperature limitations.
   d. None of the above.
8. The optical coupler is used to...
   a. assure electrical coupling only between stages.
   b. reduce output voltage and current.
   c. isolate one circuit electrically from the other.
   d. None of the above.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-06

DIGITAL TECHNIQUES

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INTRODUCTION

This module will introduce basic stages and devices that make up the majority of digital circuitry. The devices' operation theory is discussed, but electron theory is deleted. An understanding of stage operation is imperative to appreciating the function of such devices. Particular attention should be given to mathematical operation.

PREREQUISITES

The student should have completed one year of algebra and should also be familiar with the concepts of direct current and alternating current electronics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Discuss how AND gates operate.
2. Discuss how OR gates operate.
3. Discuss how inverters operate.
4. Compare NAND and NOR gates to AND and OR gates.
5. Read truth tables for AND, OR, inverter, NAND, and NOR gates.
6. Discuss latch flip-flop operation.
7. Discuss D flip-flop operation.
8. Discuss JK flip-flop operation.
9. Read truth tables for latch, D, and JK flip-flops.

DIGITAL TECHNIQUES

Modules ED-01 – ED-06 of Electronic Devices and Systems have dealt primarily with analog electronic theory. Analog refers to electronic circuits that have a continuous signal. Figure 1 demonstrates this kind of signal. An analog signal changes its value gradually at varying rates, but does not change instantaneously from one value to another.

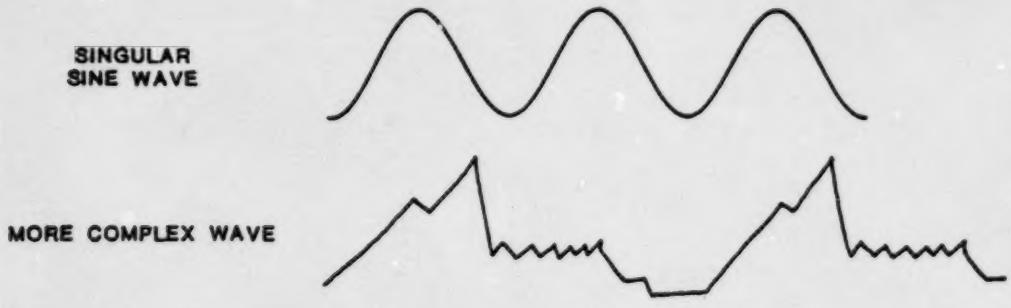


Figure 1. Analog Signals.

An example of an instantaneously-changing signal is shown in Figure 2. This signal type is usually called digital. Figure 2 shows the signal changing instantly from one value to another. The signal is in one of two states, low or high. As long as these two values maintain the same individual levels and have the same relationship in value to each other, this is called a bistate signal. The term "binary" is also used to represent a bistate signal. This term, derived from the "bi" of bistate, infers two signal states.

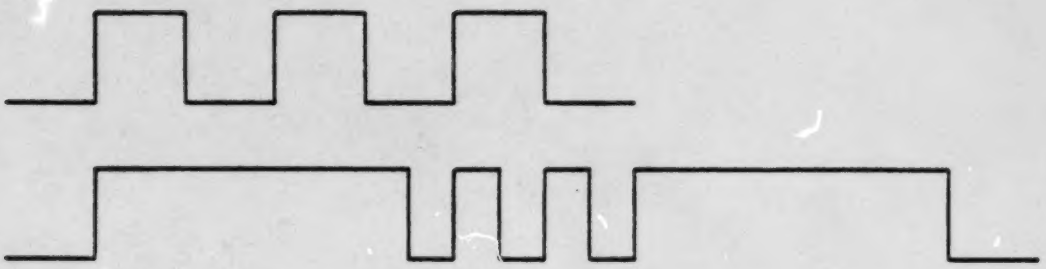


Figure 2. Instantaneous Change (Digital).

Digital signals are a string of HIGH-LOW voltage values that change in discrete steps. Usually the HIGH-LOW voltage levels are pre-chosen values established by design and remain these values throughout a given piece of equipment. Any electronic equipment containing purely digital values is digital or pulse equipment. The digital signal will be discussed throughout this module and will be called a digital or binary signal.

Most contemporary digital equipment – including computers – uses digital signals. A basic understanding of the devices used in such equipment (and the purpose of each device) is important to understanding digital electronics.

PRIMARY BINARY LOGIC DEVICES

Each stage within a digital system must be able to accept and pass a bistate signal. The transistor is the primary device used for this function.

In analog circuits, a transistor operates as OFF, LOW conduction, MEDIUM conduction, or HIGH conduction. A digital circuit only requires an OFF or ON state. This simplifies

the circuit required in digital equipment. A digital stage acts like a light switch, capable of being either OFF or ON.

BASIC LOGIC FUNCTIONS

Digital electronic equipment circuits perform only one or two general functions: decision-making or memory. Both accept digital or binary inputs and produce digital or binary outputs.

DECISION-MAKING

Decision-making circuits make decisions based on two or more inputs. The electronic device used for decision-making is called a gate. A gate is a device that has two or more input leads. The gate receives one digital signal on each lead, and usually has one output lead that produces an output signal resulting from the states of the inputs. Figure 3 shows the basic gate symbol with input and output leads.

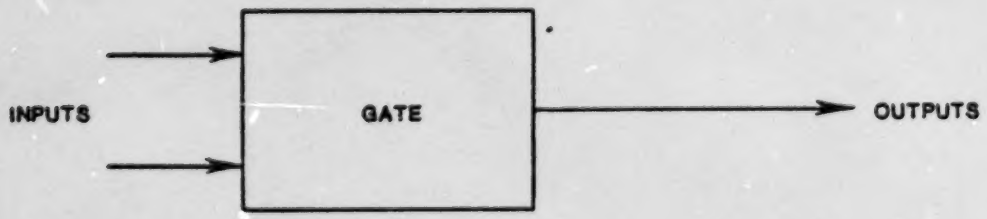


Figure 3. Block Diagram, Gate Symbol.

This symbol represents any decision-making stage. Gates always have two or more inputs.

Two basic decision-making circuits have been developed to perform decision tasks. These are the AND and OR gates.

AND Gate

All inputs to the AND gate must be the same to produce an output. Positive logic will be used to demonstrate AND gate operation. In positive logic, input can be HIGH or LOW. HIGH input is stated as logic 1. LOW input is stated as logic 0. Actually, these two states are voltages placed on each input that represent the desired state. Five volts and zero volts are most common, and will be used to describe AND gate operation. Figure 4 shows the proper circuit diagram symbol and demonstrates AND gate logical operation.

Figure 4. AND Gate.

For the AND gate to have a HIGH (or logic 1) output, both inputs A and B must also have a HIGH (or logic 1) output. This means that, if 5 volts represent HIGH (or logic 1), inputs A – as well as B – must have 5 volts applied. All other combinations possible for inputs A and B will not result in a HIGH (or logic 1) output.

The input conditions and output results are summarized on a chart called the truth table, which gives all input conditions and lists what will result at the outputs. Figure 5 shows a truth table for the AND gate shown in Figure 4.

INPUTS		OUTPUT
A	B	C
0	0	0 (LOW)
0	1	0 (LOW)
1	0	0 (LOW)
1	1	1 (HIGH)

0 = LOW
1 = HIGH

Figure 5. Truth Table.

This table shows that output is HIGH only when input is HIGH. Even when one input is HIGH, the output is still LOW. When both inputs are LOW, the output is LOW. A truth table can also be written with the inputs and output shown as voltages. Figure 6 illustrates how this is done.

INPUTS		OUTPUT
A	B	C
0V	0V	0V
0V	5V	0V
5V	0V	0V
5V	5V	5V

Figure 6. Voltage Truth Table (AND Gate).

Again, this table shows that both inputs must be HIGH for a HIGH output to occur. Output is 5 volts when both inputs are 5 volts. All other input conditions will result in 0 volts at output.

AND gates are manufactured with different numbers of inputs. Two-input, 4-input, 6-input, and 8-input AND gates are common. Circuit design determines how many are used.

Because AND gates are sealed in an opaque plastic case, it is not practical to look at the actual circuitry used to create the AND function. The manufactured case has as many as four separate AND gates enclosed. Leads for the inputs and outputs are brought out of the case – as well as the connections to which operating voltages are applied. Figure 7 shows a four, or quad, AND gate chip package.

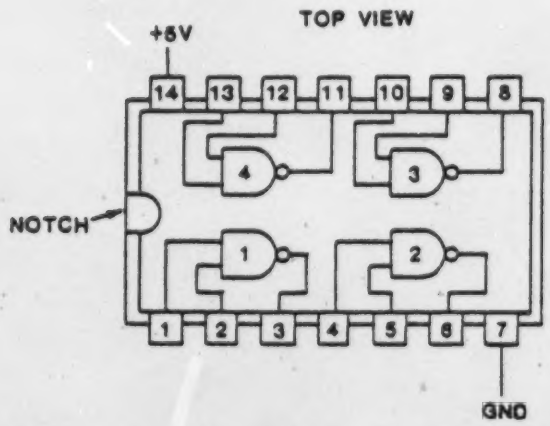


Figure 7. Pin Connections for 7400 IC.

The 5 volts connected to pin 14 are applied to operate transistors inside the gates – the 5 volts are not applied to the inputs for a HIGH condition. Likewise, the ground applied to pin 7 is necessary for operation of gate transistors. The ground is not to be construed as the 0 volts needed for the input LOW condition. Separate input signals are applied to the inputs to provide input states.

A modification of the AND gate is the NAND gate. The AND gate is converted to NAND gate by changing the output to the opposite state. This is achieved by placing an inverter on the output of the AND gate. An inverter is a sealed plastic case transistor stage that will change a HIGH (or 5 volts) to a LOW (or 0 volts), or vice versa. Figure 8 shows the inverter symbol.

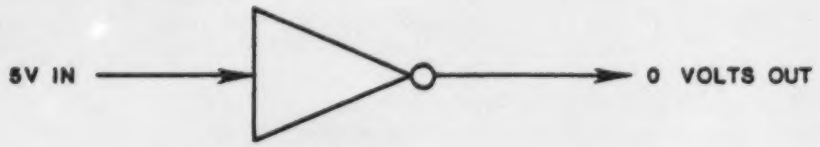


Figure 8. Inverter symbol.

Figure 8 clearly shows the transition from a HIGH input to a LOW output. Inverters do not make decisions. Inverters simply convert input to the opposite output.

The NAND gate symbol with inputs and outputs is shown in Figure 9. Figure 9b shows an expanded view that includes the inverter.

AND gate and NAND gate truth tables are similar. Figure 10a shows the truth table for an AND gate with inverter. The output of the AND gate is the input of the inverter; the inverter output is the final output of the NAND gate. Therefore, the truth tables of both may be combined, as shown in Figure 10b, because the NAND gate is a negative output AND gate. Also, NAND gate output is always opposite AND gate output, because of the action of the inverter attached to the AND gate output.

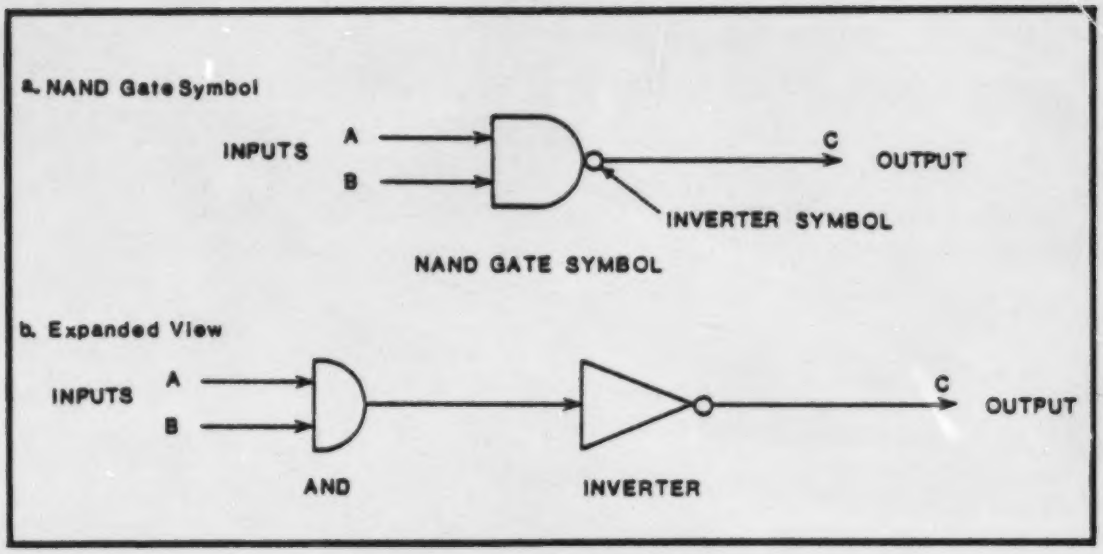


Figure 9. NAND Gate Symbol Expanded.

AND Gate Truth Table		
Input		Output
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Inverter Truth Table	
Input	Output
0	1
0	1
0	1
1	0

a. Truth Table for AND Gate, with Inverter

b. Combined Truth Table

NAND Gate			
A	B	Inverter Input	Inverter Output
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

Figure 10. NAND Gate Truth Table.

OR Gate

Somewhat similar to an AND gate is the OR gate. OR gates also have multiple inputs and a single output. Like AND gates, OR gates are encapsulated in plastic chips, with up to four gates in each chip. The major difference between the two types of gates is in the logic operations they perform.

A truth table can best describe the OR gate. Figure 11 shows the OR gate symbol and the corresponding truth table.

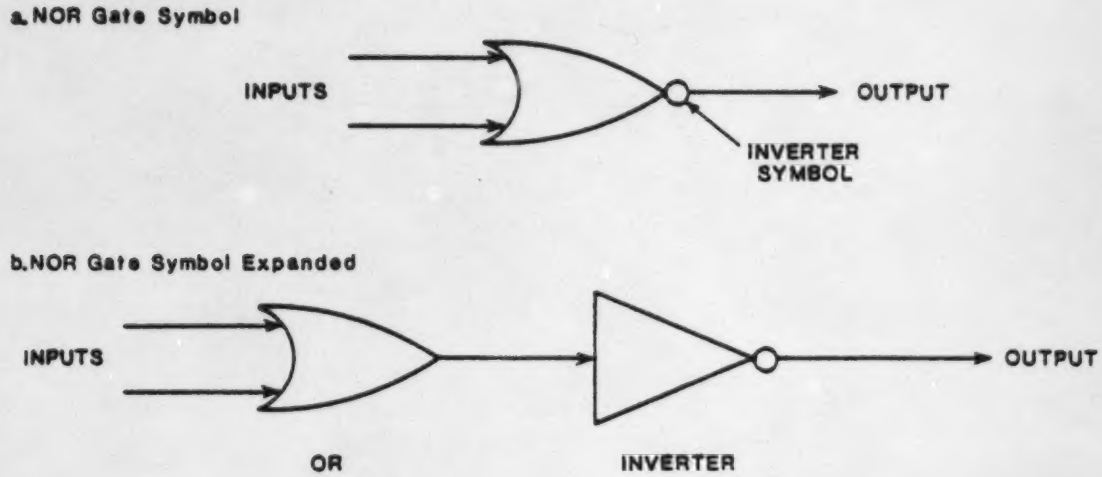
Inputs		Output
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

Figure 11. OR Gate Symbol and Truth Table.

When either OR gate input is HIGH, output is HIGH. It does not matter which input is HIGH, the result is a HIGH output. As in the AND gate, OR gate output will be LOW when both inputs are LOW – and HIGH when both inputs are HIGH.

By placing an inverter at the output of the OR gate, a negative output OR gate is created. Figure 12 describes

this newly-created gate, called a NOR gate.



OR Gate		
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

Inverter	
Input	Output
0	1
1	0
1	0
1	0

Combined Truth Table			
A	B	Inverter Input	Inverter Output
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

Figure 12. NOR Gate Symbol and Truth Table.

The output of the OR gate is the input of the inverter; the inverter output is inverted, compared to its input. All NOR gate outputs are opposite from OR gate outputs.

GATE APPLICATION

When gates are combined, the resulting circuits can perform a variety of logic operations. One use of such gates is shown in Figure 13.

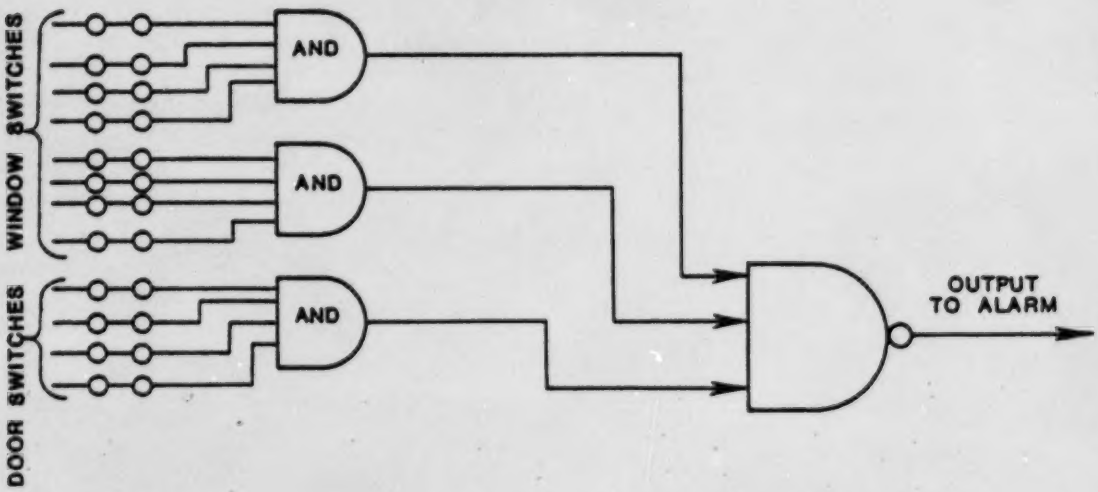


Figure 13. Burglar Alarm.

When switches are closed, output from the AND gates is binary 1. When NAND gate output remains LOW (0), no alarm will sound. If any door or window is open, one of the NAND gate inputs will be LOW. This causes the NAND gate output to be HIGH, which sounds the alarm. Other applications will be discussed in Module ED-08, "Digital Systems."

MEMORY

All gate operations discussed so far in this module have been decision-making operations. Gates can also be used to store binary conditions or data. Such circuits are called flip-flops and registers. Flip-flops are binary-storing, memory-retaining circuits that incorporate several gates to perform such a task. Registers are multiple flip-flops used to store more than one piece of binary information. Each flip-flop stores and retains one piece of binary data as one of several flip-flops. The net result from multiple flip-flops is a binary word of some size. A binary word is several bits of binary information.

Most memory stages are made up of one of three different types of flip-flops: the latch flip-flop, the D flip-flop, and the JK flip-flop. Each of these devices will be explained in their order of difficulty. A group of flip-flops of given types can be arranged to create more complex circuits. These circuits will be discussed in Module ED-08, "Digital Systems."

The Latch Flip-Flop

The latch flip-flop is often called an RS flip-flop. It is a memory device with two inputs and two outputs. The term "flip-flop" implies a two-state device. A latch flip-flop is a two-state device with two inputs and two outputs. The signals placed on the inputs cause the flip-flop to do one of two things.

1. Change the outputs to the opposite state.
2. Make no change of the output.

Therefore, operation of the latch depends upon input signals. Figure 14 illustrates the latch using 2 NAND gates to make the flip-flop. Figure 15 illustrates operation of the latch.

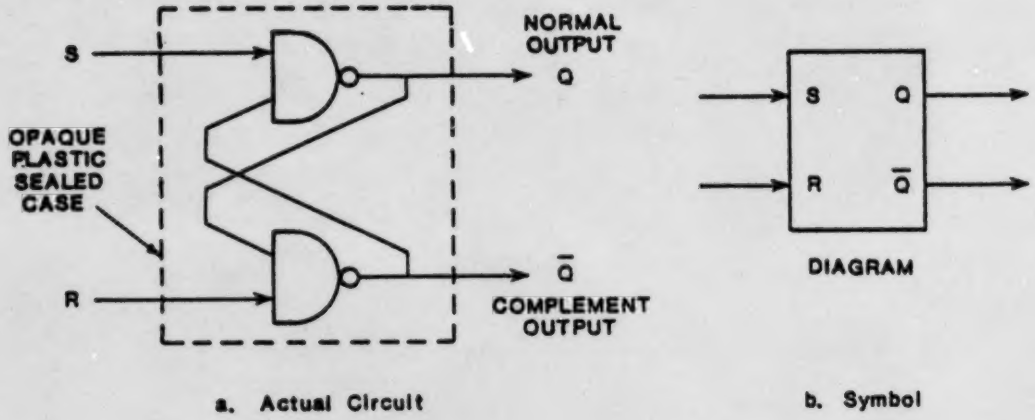


Figure 14. Latch Flip-Flop.

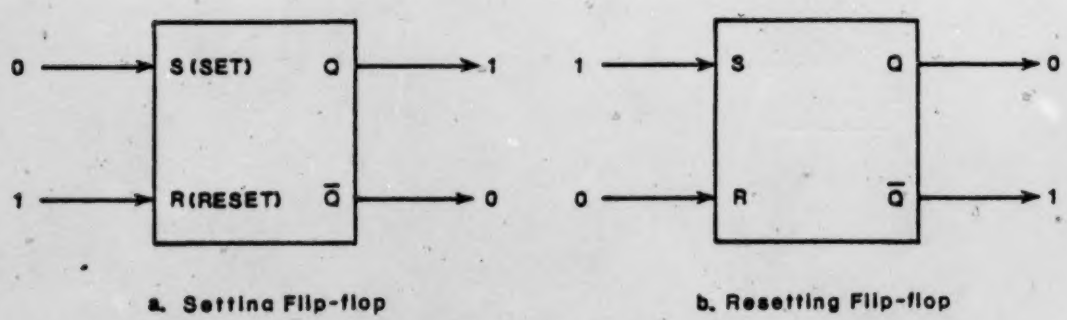


Figure 15. Operation of the Latch Flip-Flop.

When applying input signals, it is necesary to be certain that the S and R inputs have opposite states. The application of inputs will then either set or reset the

flip-flop, depending upon input states. Figures 15a and 15b show that the lead receiving a binary 0, or LOW, will cause the output Q to become what that lead represents. For example, if a 0 is applied to the S (or set) lead, the output Q will become set (or binary 1). Conversely, when a 0 is applied to the R (or reset) lead, the output Q becomes a reset (or binary 0). The $\overline{Q}$ output is pronounced "not Q" or "Q not," which indicates it is always opposite the Q output. The $\overline{Q}$ output, then, is the complement of the Q output. Figure 16 shows legal input combinations and output results summarized in a truth table. The truth table summarizes input conditions and output results of a logic circuit.

Inputs		Outputs		
S	R	Q	$\overline{Q}$	Comments
0	0	1	1	Not Allowed
0	1	1	0	Set
1	0	0	1	Reset
1	1	X	$\overline{X}$	Idle States

Figure 16. Legal Input Combinations and Output Results.

Because of the design of the NAND gate flip-flop, when inputs S and R are LOW (or binary 0), both Q and $\overline{Q}$ will become HIGH, a state which is not valid as a legal output for the latch. Outputs Q and $\overline{Q}$ must always be opposite from, or a complement of, each other.

When the S input is a binary 0 and the R input is a binary 1, the Q output will become a binary 1 and reflects a setting of the flip-flop. The $\overline{Q}$ output will be a binary 0.

When the S input is a binary 1 and the R input is a binary 0, the Q output becomes a binary 0 – reflecting a resetting of the flip-flop. The $\overline{Q}$ output then becomes a binary 1.

When the S input and the R input both are a binary 1, the Q and $\overline{Q}$ output states will be dependent upon the states established during the last input condition. Therefore, when both inputs are binary 1, the flip-flop preserves last previous output conditions. These input conditions (S = 1, R = 1) are used when the latch is placed in the idle (or unchanged) condition.

The Latch Application

One of the uses of the latch is to eliminate switch debouncing. Switch debouncing is a condition that occurs when a switch is transferred from one position to another. Figure 17 illustrates what happens electrically when a switch is changed from one position to another. The switch is used to change (or switch) from 5 volts to 0 volts, or back. (These are the voltages used to provide inputs to the gates that were discussed in the first part of this module.)

Because of the spring action in some switches and the human finger pressure in others, the switch contacts will bounce – causing multiple makes and breaks – when the switch is changed from one state to the other. The input to the gate will not know what state it should be in until the switch settles down. If the gate stage cannot tolerate such erratic change, the switch bounce must be removed. A latch circuit is used to assure a solid OFF-ON or ON-OFF action in this case.

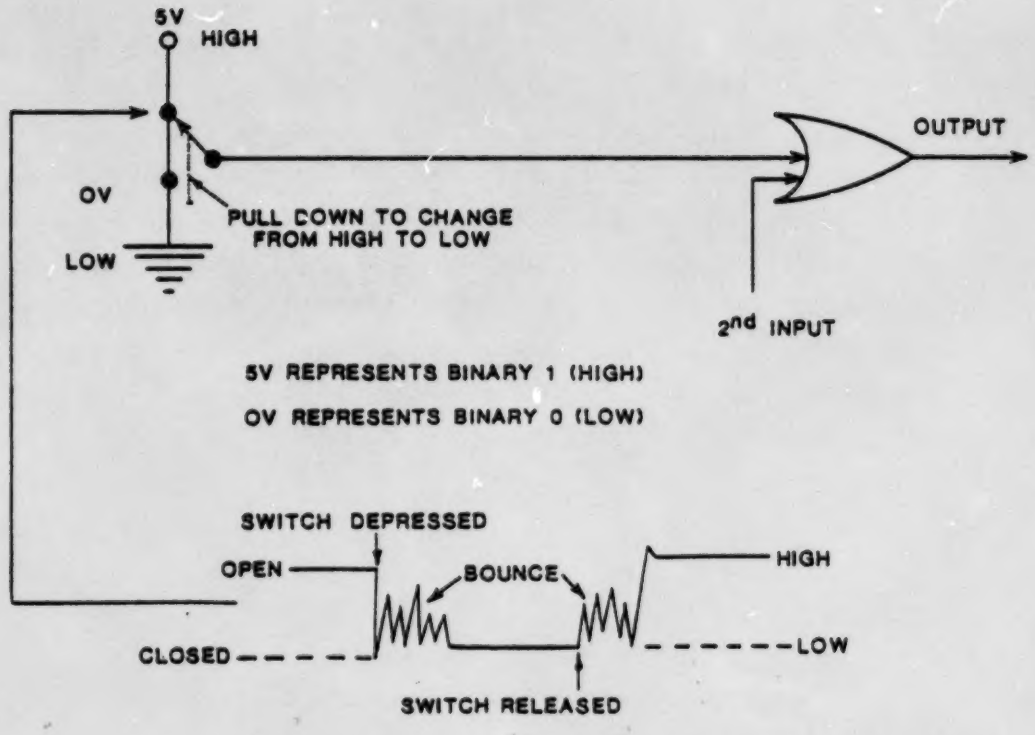


Figure 17. Switch Debouncing.

The D Flip-Flop

The D flip-flop gets its name from the word, "Data." A series of ON-OFF (1s and 0s) pulses, often called Data, is applied to an input called the D input.

The D flip-flop also has a T-input, which is connected to a signal called a toggle signal. The toggle input signal determines whether the Data on the D input will or will not reach the output. The toggle signal can be any combination of HIGH (1) or LOW (0) signal pulses. The signal pulses are determined by the purpose of the D flip-flop.

Figure 18 further illustrates operation of the D flip-flop.

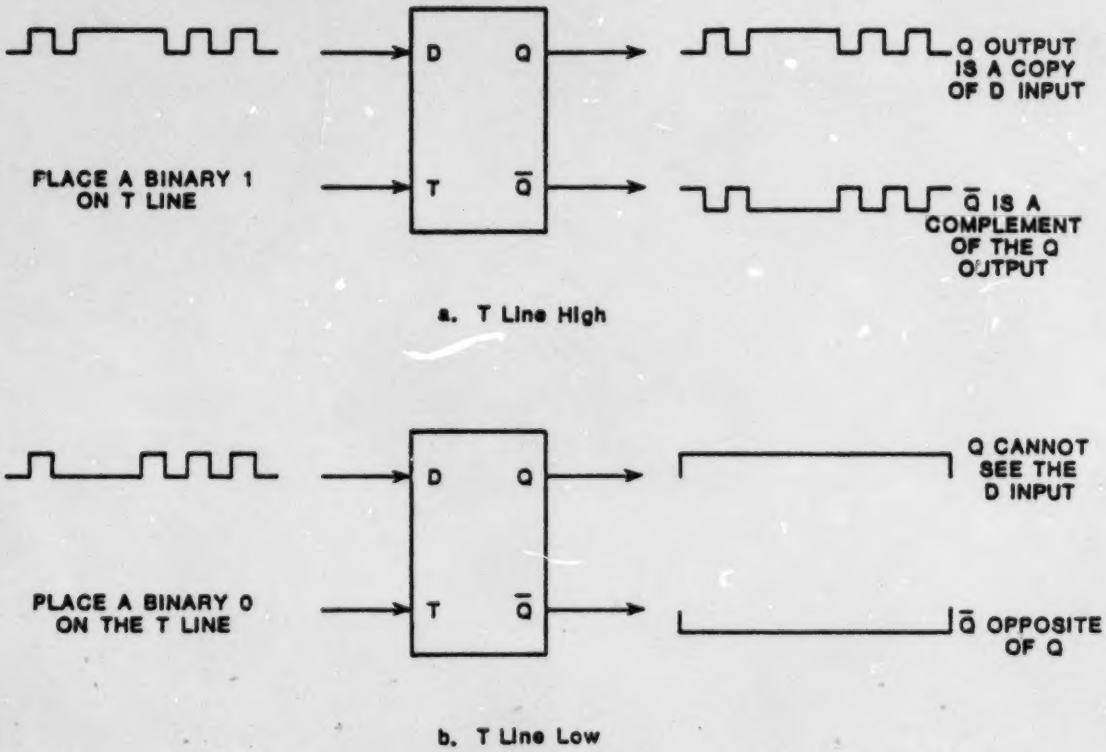

D
Q
T
$\overline{Q}$
Q OUTPUT IS A COPY OF D INPUT
PLACE A BINARY 1 ON T LINE
$\overline{Q}$ IS A COMPLEMENT OF THE Q OUTPUT
a. T Line High
Q CANNOT SEE THE D INPUT
PLACE A BINARY 0 ON THE T LINE
$\overline{Q}$ OPPOSITE OF Q
b. T Line Low

Figure 18. D Flip-Flop Operation.

Figure 18a shows that when the T line is HIGH, whatever is on the D line will pass to the Q output; the complement will be passed to the $\overline{Q}$ output.

Figure 18b shows that when the T line is LOW, neither the Q or $\overline{Q}$ outputs will be a copy of the D input. When the T line is LOW, the flip-flop is held in the preceding output condition.

The operation of the D flip-flop acts like a one-way, ON-OFF switch to the signal on the D line input.

D Flip-Flop Application

D flip-flops are usually used to store data for a given time period. Figure 19 describes the use of four such flip-flops to store conditions of a 4-switch arrangement. The switches are in a preset position and may be changed from time to time. Each time the switch states must be seen, the T line is toggled HIGH (binary 1 or 5 V). The switch conditions tied to the D line will then be transferred to the Q output and the complement to the $\overline{Q}$ output.

Figure 19 illustrates a circuit called a 4-bit register. The 4 flip-flop registers store each of the four bits of switch information when the respective T lines are placed at binary 1. If the T lines are placed to binary 0, outputs retain the last set of switch conditions that occurred when the T lines were HIGH. This is an important point, because the D flip-flop – like the latch – is a memory-storing, memory-retaining device.

A SINGLE POLE
DOUBLE THROW SWITCH

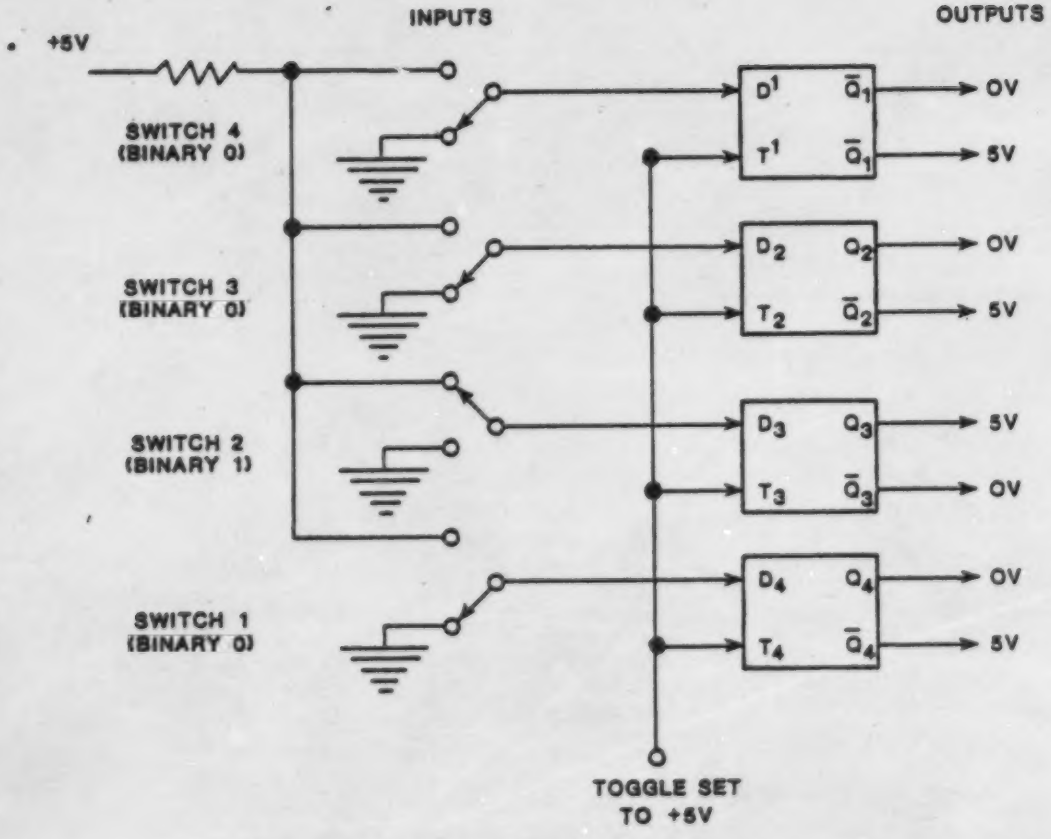


Figure 19. D Flip-Flop Application.

JK Flip-Flop

The JK flip-flop is the most versatile binary storage flip-flop. It not only can perform RS flip-flop and D flip-flop functions, but others as well. Essentially, the JK flip-flop has two sets of inputs and a toggle input. These inputs will be discussed.

The JF flip-flop is really two flips, one driven by the other. Figure 20 shows the general circuit.

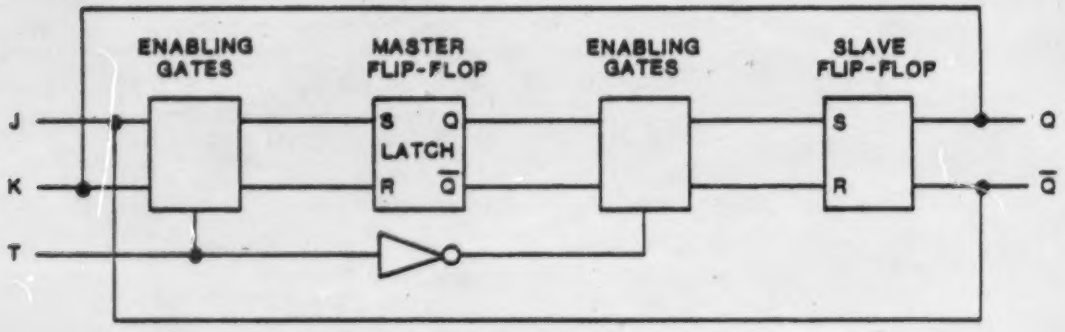


Figure 20. JK Flip-Flop Block Diagram.

Figure 20 illustrates a master and a slave latch flip-flop. A latch is a set-reset type of flip-flop. An enabling gate that is controlled by the toggle pulse T precedes each flip-flop. The T pulse is determined by the design of a particular circuit where the JK flip-flop is used.

If the T pulse is set at binary 1, the signal on the J and K inputs is read by the master flip-flop. As long as the T pulse remains HIGH, nothing further will occur; the master flip-flop retains the conditions on the J and K inputs in its memory.

When the T pulse goes LOW, the memory of the master flip-flop is transferred through the second set of enabling gates to the slave flip-flop – and then immediately to the Q output. As long as the T pulse stays LOW, the slave flip-flop (and thus the outputs) will remain as established by the previous JK inputs. Any further changes on the JK inputs (while the T pulse is LOW) will not be read by the master flip-flop. This is because with a LOW T pulse, the enabling gates prior to the master flip-flop are disabled, and act as an open switch.

Close inspection will reveal that the JK inputs' condition will be transferred to the Q output only after two changes (a HIGH and a LOW) of the T line have occurred.

The master and slave flip-flops are either set or reset as a result of valid JK inputs and T pulse action. The JK flip-flop can store only a binary 1 or a binary 0. Therefore, the JK flip-flop is primarily a memory device – as were the latch and D flip-flops.

The symbol for the JK flip-flop is shown in Figure 21. Also shown are two additional leads which are the S (set) and C (clear) inputs. These leads are used to pre-establish the slave flip-flop state. This is especially important when several flip-flops are used to read several inputs. This application will be discussed.

If the JK leads are not used, and only the T pulse (alternating) is applied, the JK flip-flop can be used as a divide-by-two clock. A clock is a device or stage that puts out a continuous square wave pulse at a given rate.

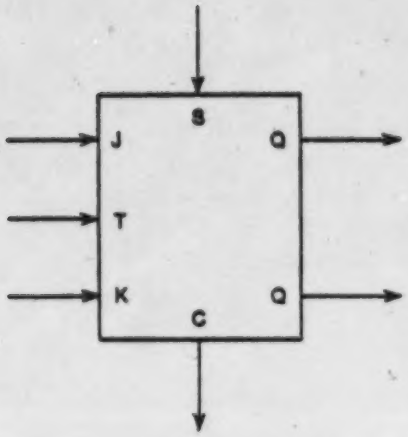


Figure 21. JK Flip-Flop Symbol.

For review, Figure 22 illustrates the appearance of a square wave pulse signal. The S and C leads, as well as the J and K leads, usually are all tied to 5 volts for a divide-by-two clock, with only the T lead being pulsed.

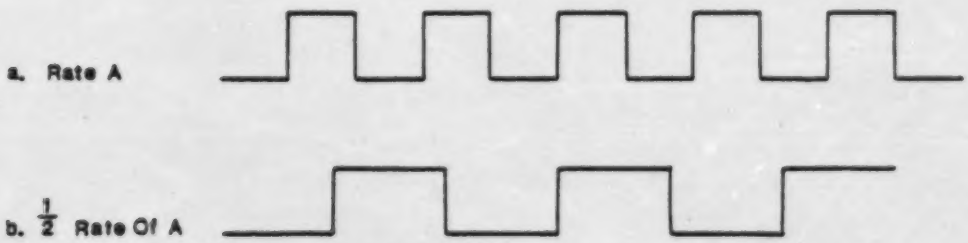


Figure 22. Square Wave Signal.

Figure 22a illustrates the appearance of the input on the T lead and Figure 22b shows what the output Q looks like when the JK flip-flop operates as a divide-by-two stage.

JK Flip-Flop Applications

Applications mentioned earlier, such as the latch and D flip-flop, can also be performed. Latch, D, and JK flip-flop applications will be performed in the laboratory which follows.

EXERCISES

1. Which items below are digital? Which are analog?
   a. Ammeter _____.
   b. House lights _____.
   c. Pressure gage _____.
   d. Water level meter _____.
   e. Electric clock _____.
2. Is an a.c. voltage analog or digital? _____.
3. Is a d.c. voltage analog or digital? _____.
4. Four wires (A through D) carry voltage levels representing a binary number. Assuming wire A is the leftmost level – and level D the rightmost level – what number in binary does it represent? Use 1s and 0s to represent the levels shown below.

	A	B	C	D
A + 5V	_____	A		
B 0V	_____	B		
C 0V	_____	C		
D + 5V	_____	D		

5. Using knowledge gained from this and other modules, draw the logic diagram, using AND or OR gates, for the following switching circuit.

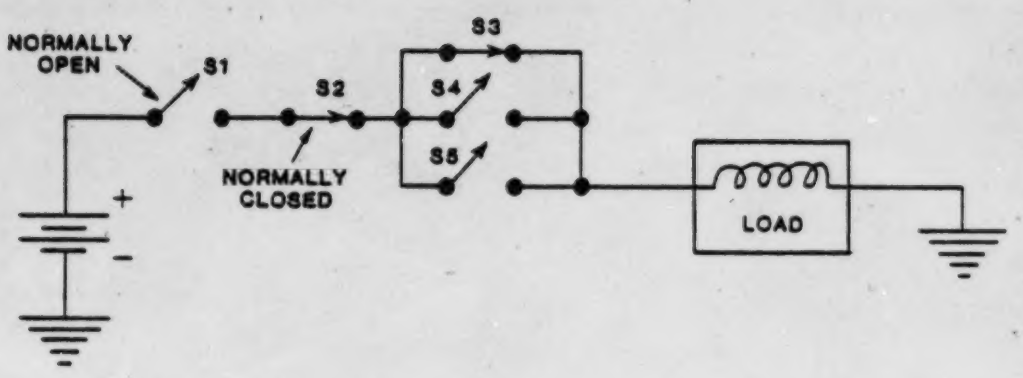


Figure 23. Switching Circuit.

6. Which of the following is common for the latch, D, and JK flip-flops?
   a. All have same kinds of inputs (example JK inputs).
   b. All have same kinds of outputs (example Q & $\overline{Q}$).
   c. All have enabling gates.
   d. All have SR flip-flops.
7. A 4-D flip-flop register is storing a binary number. The flip-flops are labeled A, B, C, and D from left to right. If the Q output is used on each flip-flop, and the following Q states exist, what binary number is represented? (Use 1s and 0s.)

   A = set B = reset C = set D = reset

   binary number _____ _____ _____ _____
   A B C D

LABORATORY MATERIALS

Laboratory 1

1 7400 TTL NAND gate integrated circuit.
1 5-volt regulated d.c. power supply (500 mA).
1 digital trainer, with data and logic switches and LED indicators. (Suggest the Heathkit ETW-3200 Digital Trainer; Heathkit Corp., Benton Harbor, Michigan. Trainer includes +5 volt power supply.)

Laboratory 2

1 7400 NAND gate integrated circuit.
1 5-volt regulated d.c. power supply (500 mA).
1 digital trainer with data and logic switches and LED indicators. (Suggest the Heathkit ETW-3200 Digital Trainer; Heathkit Corp., Benton Harbor, Michigan. Trainer includes +5 volt power supply.)

LABORATORY PROCEDURES

LABORATORY 1. OPERATION OF LATCH FLIP-FLOP.

1. Construct the circuit shown in Figure 24.
2. With the logic switches in the $\overline{A}$ and $\overline{B}$ positions, apply power to the circuit.
3. It is important to note the output states as power is applied. Record answers in the spaces that follow:

   With power up:

   LED indicator 1 = _____ (Q output).
   LED indicator 2 = _____ ($\overline{Q}$ output).

(These states are the previous states. Once the input logic switches are changed, these states will change.)

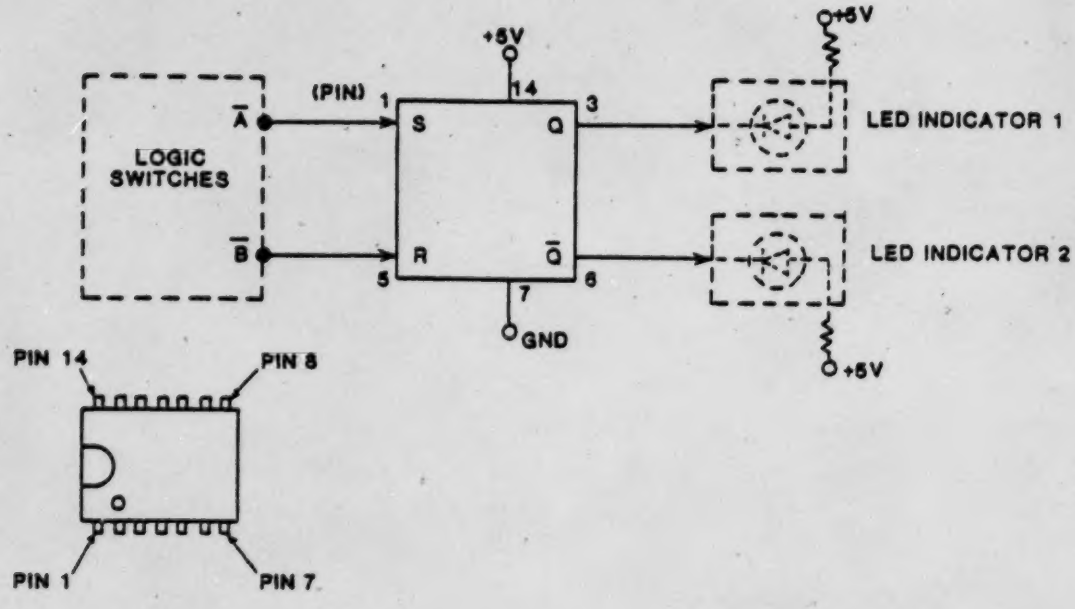


Figure 24. (NAND Gate) SR Flip-Flop.

4. Using the latch truth table shown in Data Table 1, apply the combinations shown for different input conditions and record the LED indicator results in the output column of the table. Remember that:

   LED ON = binary 1.

   LED OFF = binary 0.

LABORATORY 2. OPERATION OF D FLIP-FLOP.

1. Wire the circuit shown in Figure 25.
2. Apply +5V to the circuit from d.c. power supply. (This +5V is applied to pin 14.)
3. Place input data switch 1 and 2 to the LOW or binary 0 state (0 volts).
4. Apply the inputs shown in the truth table in Data Table 2. Record the Q and $\overline{Q}$ results in the output column. Remember that:

   LED ON = binary 1.

   LED OFF = binary 0.

   The JK flip-flop will be discussed in further detail in Module ED-08.

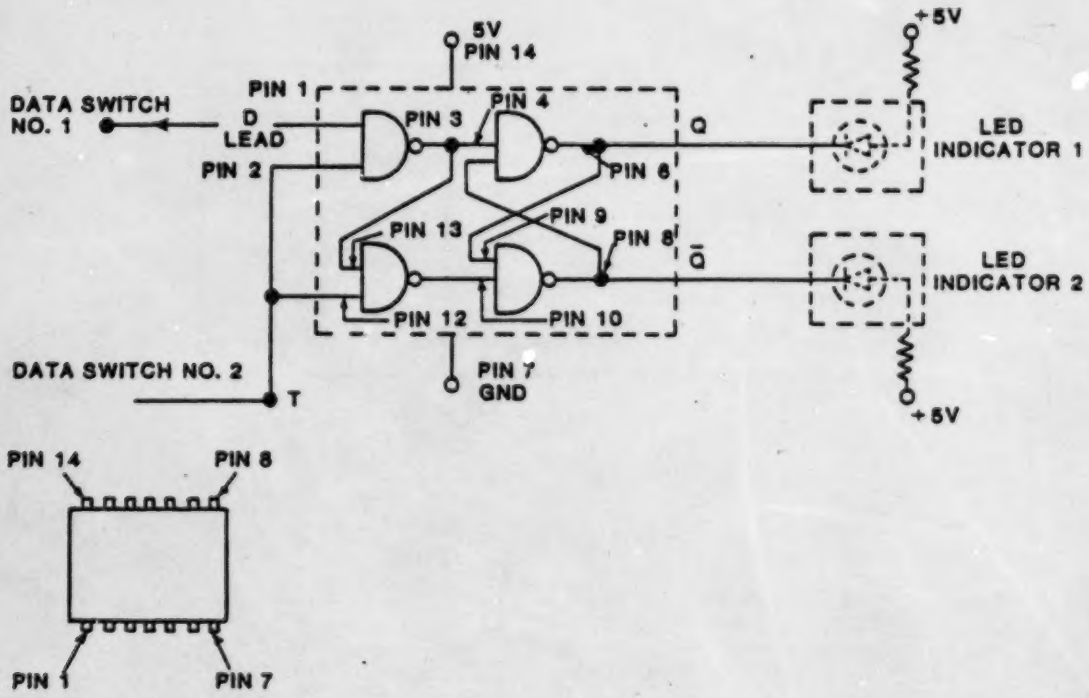


Figure 25. NAND Gate Flip-Flop.

DATA TABLES

LABORATORY 1. OPERATION OF LATCH FLIP-FLOP.

TRUTH TABLE:

$\overline{A} = 0$
$\overline{B} = 0$
$A = 1$
$B = 1$

Input Conditions		Output Conditions		State (Set or Reset)
$\overline{A}$	$\overline{B}$	LED 1	LED 2	
0	0			
0	1			
1	0			
1	1			

LABORATORY 2. OPERATION OF D FLIP-FLOP.

TRUTH TABLE:

	Input Switches		Output LEDs	
	D	T	Q	$\overline{Q}$
Step 3 →	0	0		
	0	1		
Step 4 →	1	0		
	1	1		

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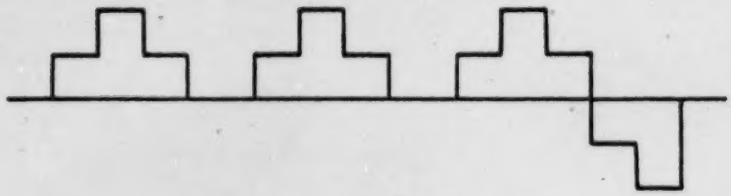
Floyd, Thomas L. Digital Logic Fundamentals. Charles E. Merrill Publishing Company (A Bell & Howell Co.).

Heathkit Learning Publications. Digital Techniques. Benton Harbor, MI: Heath Company, 1978.

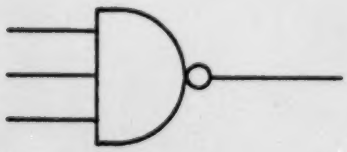
Maloney, Timothy J. Industrial Solid-State Electronics Devices and Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc.

1. The waveform in the accompanying illustration is...
   a. Analog.
   b. Digital.



Waveform for Question 1.

2. The logic function being performed in the illustration shown is...
   a. AND.
   b. $\overline{\text{AND}}$.
   c. OR.
   d. $\overline{\text{OR}}$.



3. The two basic, or general, kinds of logic stages are...
   _____.
   _____.

4. If the circuit shown in the illustration with question one had an inverter gate attached to its output, what function would the entire stage perform?
   a. AND.
   b. $\overline{\text{AND}}$.
   c. $\overline{\text{OR}}$.
   d. OR.

5. A burglar alarm is designed to alert a security officer if doors or windows are opened. What basic logic function is performed?

   a. AND.
   b. $\overline{\text{AND}}$.
   c. $\overline{\text{OR}}$.
   d. OR.

6. In the truth table shown, what basic logic function is being performed?

   a. Inverter.
   b. NAND.
   c. NOR.
   d. OR.

A	B	C	Output
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	1	0

7. The $\overline{Q}$ output of a flip-flop is HIGH. What binary state or condition is the flip-flop said to be in?

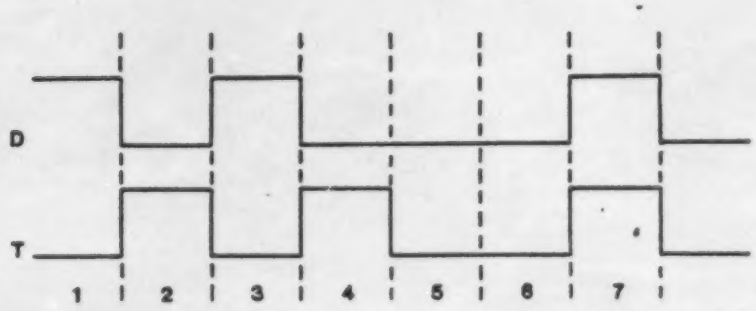
   a. Binary 0.
   b. Binary 1.

8. If a series of flip-flops are used to generate an output frequency of 250 KHz from an input of 2 MHz, how many are required (use a JK flip-flop with the J-K and S-C leads tied to binary 1)?

   a. 1.
   b. 2.
   c. 4.
   d. 8.

9. A flip-flop is the basic logic stage in which of the following types of logic operations?
   a. Sequential.
   b. Analog.
   c. a.c.
   d. Combinational.

10. Draw the output waveform for a D-type flip-flop with the D and T inputs as shown in the accompanying illustration.

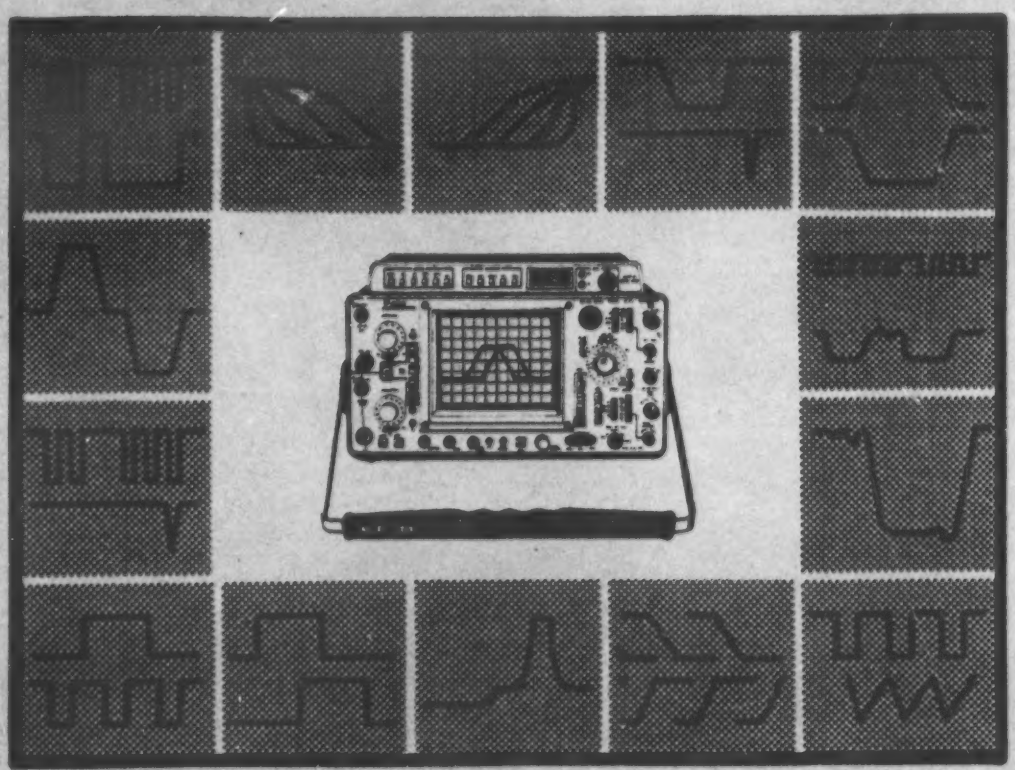


Draw output here:

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRONIC DEVICES AND SYSTEMS



MODULE ED-07

ANALOG AND
DIGITAL SYSTEMS

TECHNICAL EDUCATION RESEARCH CENTER - SOUTHWEST
4800 LAKEWOOD DRIVE, SUITE 5
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INTRODUCTION

This module presents a practical study of some of the more basic analog and digital systems on the market today. The student should be aware, however, that countless other types of analog and digital systems exist. In a course of this size it would be impossible to address each one; however, if interest is generated, the student may want to research this information. Such data can be found in libraries or computer hardware material.

It is particularly important for the student to pursue further study in areas such as digital-to-analog and analog-to-digital convertors. It is also recommended that the student keep abreast of new developments in the electronics field. Many new technologies simplify operation and extend features of analog and digital systems. Since the exercise section of this module requires that the student know some of this information, research may be begun immediately.

PREREQUISITES

The student should have completed one year of algebra, should be familiar with the concepts of direct current and alternating current electronics, and should have completed all the previous modules of this course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the functional operation of a regulated power supply.
2. Identify the different stages within an audio amplification system.
3. Explain how a signal flows through an audio system.
4. State the cases in which SCRs are used and draw the system to operate a series d.c. motor.
5. State the cases in which triacs are used and draw the system to operate a shunt a.c. motor (control the field).
6. Explain the uses of thermocouples and diode temperature probes.
7. Explain the operation of an operational amplifier temperature sensing circuit.
8. Explain the operation of a humidity controller and light-sensing system.
9. State the uses of binary counters.
10. State the uses of shift registers.

ANALOG SYSTEMS

The term "analog" refers to a method of communicating information through continuous, varying signals. This concept, which is also called "linear," may be represented by a sine wave such as that produced on an oscilloscope.

Several types of basic analog systems are described in the following paragraphs.

POWER SUPPLIES

All electronic systems require a power supply from which a direct current (d.c.) voltage is generated by converting alternating current (a.c.) to d.c. The more modern supplies have components that regulate d.c. voltage. These components, called voltage regulators, are the final stage of the power supply.

The first electronic d.c. voltage regulators that were manufactured included stages similar to those shown in Figure 1. In the figure, each block represents a stage constructed around a transistor. Therefore, earlier systems consisted of discrete components.

Recent developments, however, have led to the use of integrated circuit packages for stages. The result of this new design is a much smaller regulator. Figure 2 shows an example of an IC package regulator and how it is connected to the power supply. The 5-V regulator shown has only three leads coming out of the sealed package. The chip is located inside the sealed pacakge and, therefore, cannot be repaired; it must be replaced if failure occurs.

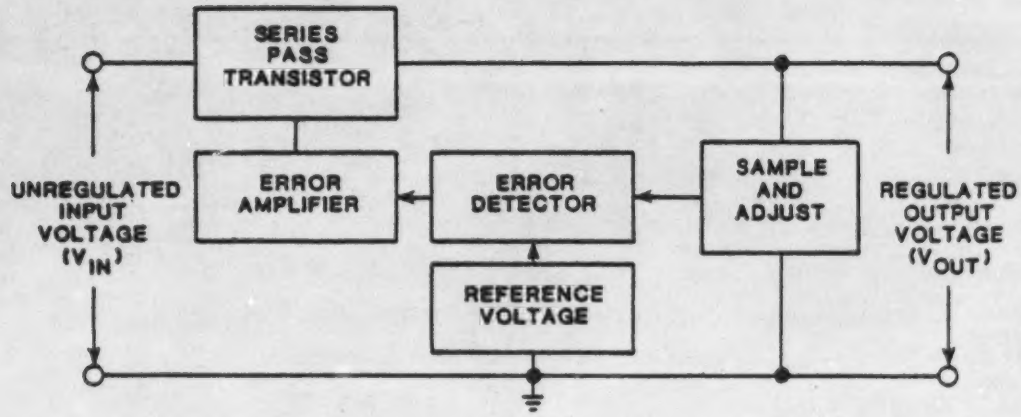


Figure 1. Electronic Voltage Regulator.

Figure 2 shows a fused 110 volts fed to a transformer (stepdown). The output from the full-bridged rectifier is first smoothed by the use of capacitor C_1. Then, the 5-V regulator removes any remaining ripple and outputs a smooth, non-changing 5-V d.c. voltage.

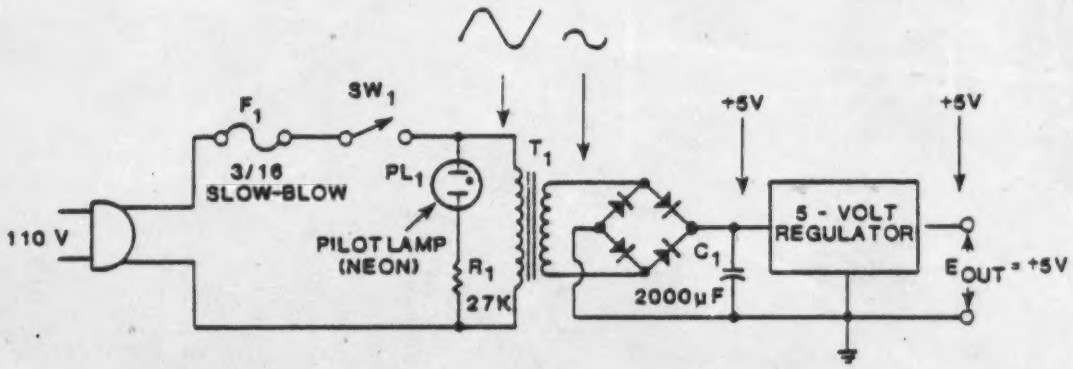


Figure 2. D.C. Power Supply with IC Package Regulator.

AUDIO SYSTEMS

Audio system amplifier frequencies range between about 20-20,000 Hz. These frequencies are the lowest of all a.c. frequencies encountered in electronics.

There are several types of systems – usually so named by the type of "between the stage" coupling used. As was learned earlier, the couplings could be of the direct current, capacitor, or transformer types. Two such examples follow:

Direct Current Coupling

Figure 3 illustrates an audio direct current coupled amplifier. (The exception is the input to the first stage and the output to the last stage.) As stated previously, a d.c. amplifier can pass either d.c. or a.c. signals, but the example shown below illustrates an amplifier passing a.c. signals.

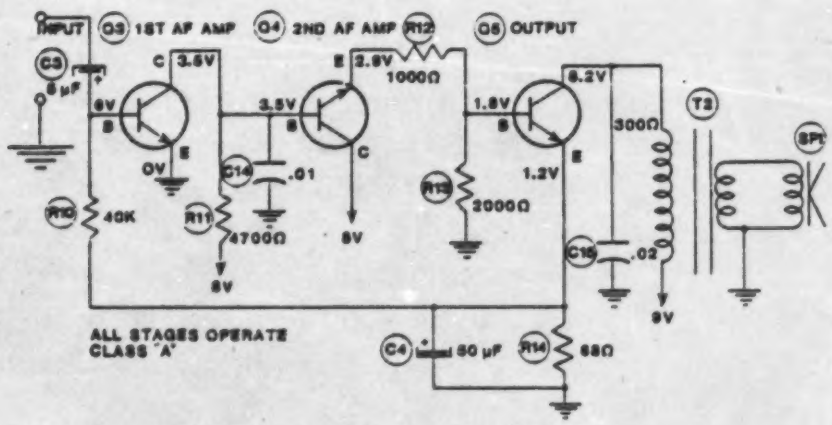


Figure 3. D.C. Coupled Amplifier.

The coupling used between Q_3 and Q_4 is simply a wire. All of the signal coming out of the collector of Q_3 will enter the base of Q_4 without any loss or decrease. There is a resistor located between Q_4 and Q_5. A review of previous information yields that a resistor passes d.c. or a.c. and alternates each equally. The resistor R_{12} will reduce the value of the signal, but it will not distort the signal shape.

The chief advantage of d.c. coupling is that the signal is not distored since a resistor alone cannot cause distortion. Direct current coupling is used in low-power applications where distortion has to be kept to a minimum.

Capacitor and Transformer Coupling

The audio system shown in Figure 4 incorporates both capacitor and transformer coupling. Close inspection reveals that Q_7 and Q_8 are Class A amplifiers, with Q_9 operating to its maximum limits (Class A) to drive the transformer primary of T_1. The secondary of T_1 has two windings, each of which provides a signal to Q_{10} and Q_{11}. These latter transistors operate Class B in such a way that Q_{10} amplifies only one-half of the signal, whereas Q_{11} amplifies the other. The outputs of Q_{10} and Q_{11} are recombined in the primary winding of T_2 and through transformer action first to the secondary and finally to the speaker.

The capacitor and transformer coupled amplifier system uses PNP transistors. PNP transistors are common; however, NPN transistors, or a combination of PNP and NPN transistors, are more frequently used in this type of system.

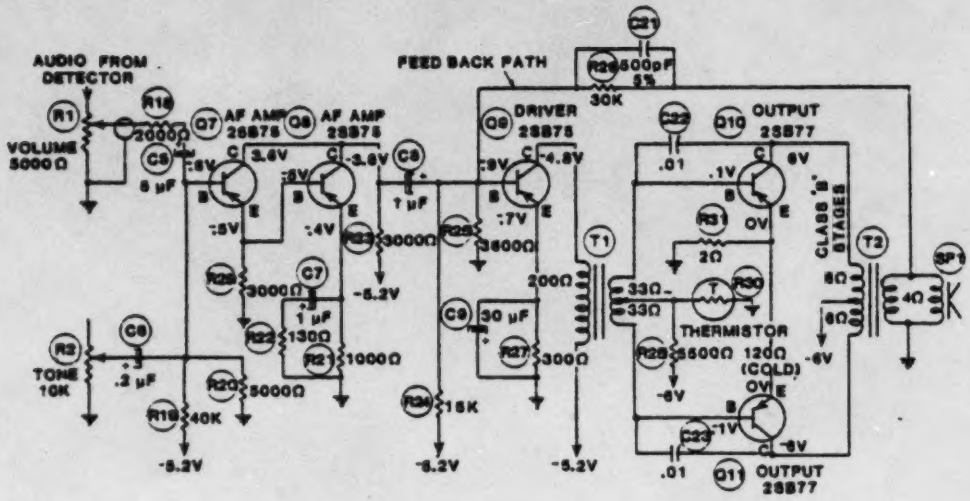


Figure 4. Capacitor and Transformer Coupled Amplifier.

Most modern systems of audio amplifiers are making the transition to the IC package area. Complete low-power amplifiers are often within the reach of a single "chip." High power amplifiers often are designed to use several chips. In very high power amplifiers, the output stages are discrete transistors because of the higher heat created.

SILICON CONTROLLED RECTIFIERS – D.C. CONTROL SYSTEMS

A variety of circuits can be derived with silicon controlled rectifiers (SCRs) to control d.c. motor circuits. Figure 5 shows a single phase half-wave speed control system for a d.c. series motor. Adjustment of potentiometer R_3 will determine the triggering of the SCR. Increasing the gate voltage will cause the SCR to fire sooner during each a.c. cycle of the power source – which means that the SCR will be

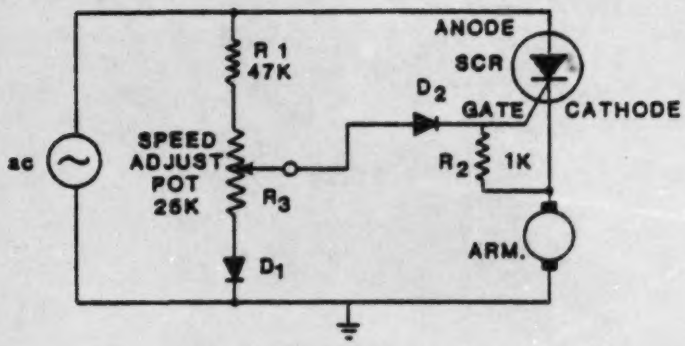


Figure 5. Series Motor – SCR Control.

"ON" for a longer period of time. Thus, the motor will run faster. Once the potentiometer is left at a predetermined adjustment, the speed of the motor will settle at one speed. Slower speeds are obtained by reducing the gate voltage. This reduction is accomplished by adjusting R_3 in the opposite direction from the one that was used to measure the speed.

Figure 6 shows a SCR control circuit that is used to control a d.c. shunt motor. Close inspection will show that a full-wave bridge rectifier provides a constant d.c. voltage to the field winding.

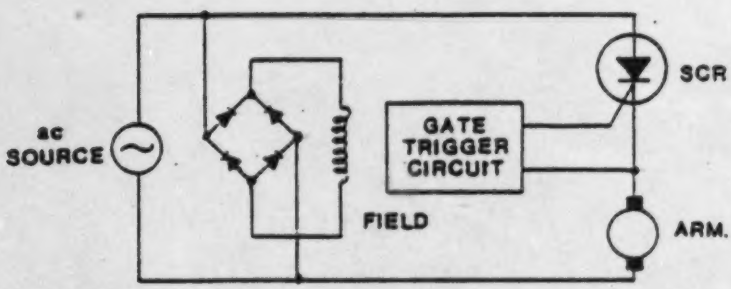


Figure 6. SCR D.C. Shunt Motor Control.

The speed of this motor is changed by controlling the "ON" time of the SCR, thus providing a given current and voltage to the armature. Because the SCR is a one-way device for current flow, adjusting the gate circuit will determine how long the SCR is ON. More current and voltage will be provided for the armature when the SCR is gated ON longer; and less current and voltage will be provided for the armature when the SCR is gated ON for a shorter period of time.

TRIACS-A.C. CONTROL SYSTEMS

Triacs are used to control the power fed to a.c. devices. Figure 7 shows a straightforward circuit functioning from an a.c. source that controls the power being fed to a lamp. Motors and other devices, of course, also can be controlled by a similar circuit. This particular circuit might be found in residential lighting systems.

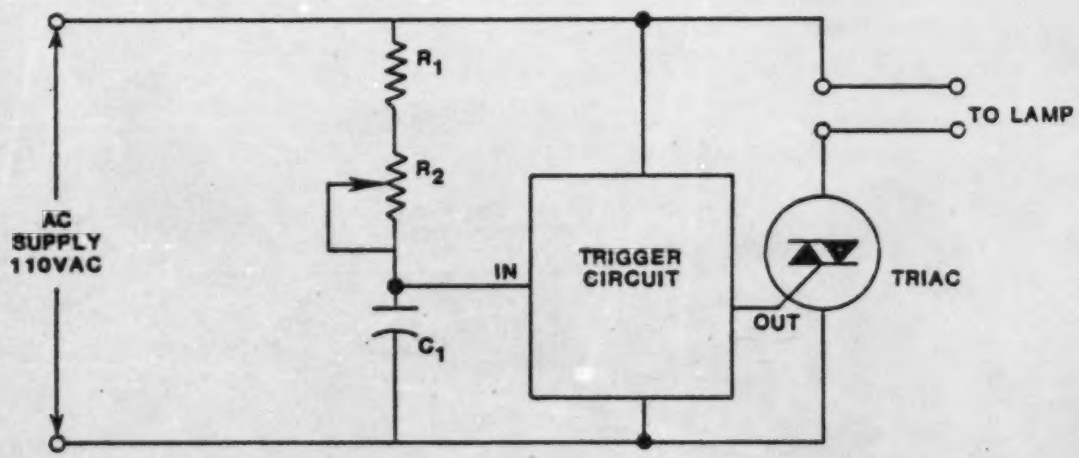


Figure 7. Straightforward Circuit From an A.C. Source.

Figure 7 shows an adjustable input to the trigger circuit so the lamp can be adjusted for various degree of brightness as desired. The voltage across the capacitor C_1 is applied to the input of the trigger circuit, which, in turn, supplies the proper triggering voltage to the triac. Depending upon the voltage applied, the lamp will be made to light at a given brilliance. Changing the adjustment of R_2 will, in turn, change the brightness of the lamp.

TEMPERATURE MONITORING SYSTEMS

The thermocouple is a popular device for measuring temperature. This device is constructed of two dissimilar wires twisted at one end. Figure 8 shows a simple system in which temperature can be measured.

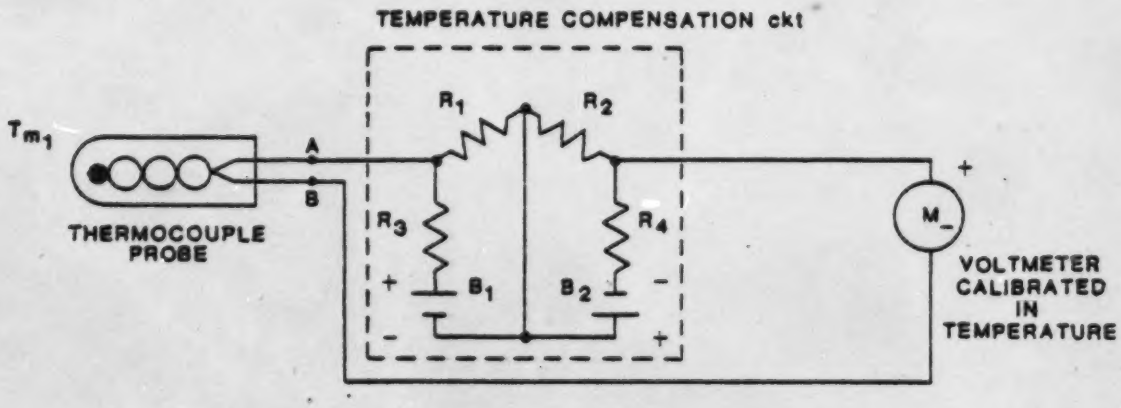


Figure 8. Thermocouple Temperature System.

Tm_1 is the temperature thermocouple. As the temperature near the probe increases, the voltage across points A and B increases. This voltage is fed to the temperature

compensation circuit. Resistor R_2 in this compensation circuit is used to compensate for non-linear characteristics in the probe. R_2, along with R_1, R_3, R_4, B_1, and B_2, provides proper voltages to the voltmeter, which is calibrated to measure the temperature from the probe.

There are four basic ranges in which thermocouples can be purchased. Figure 8 illustrates the voltage output for a given temperature range. It should be noted that these probes are for temperatures that range as high as 1400°F to almost 3000°F.

When temperatures that range below about 200°F must be measured, solid state diode probes can be used.

Silicon diodes – when heated – vary the actual resistance within their junctions. These diodes, therefore, can be used to sense temperature changes. Figure 9 shows a simple circuit using a silicon diode probe and temperature calibrated meter.

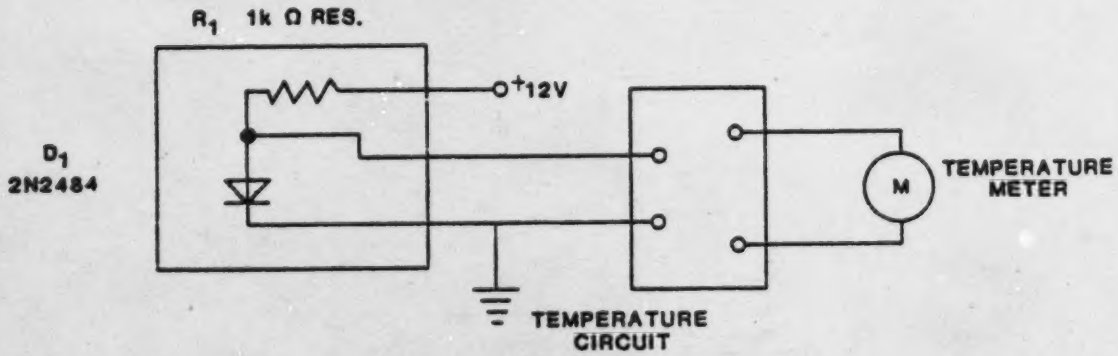


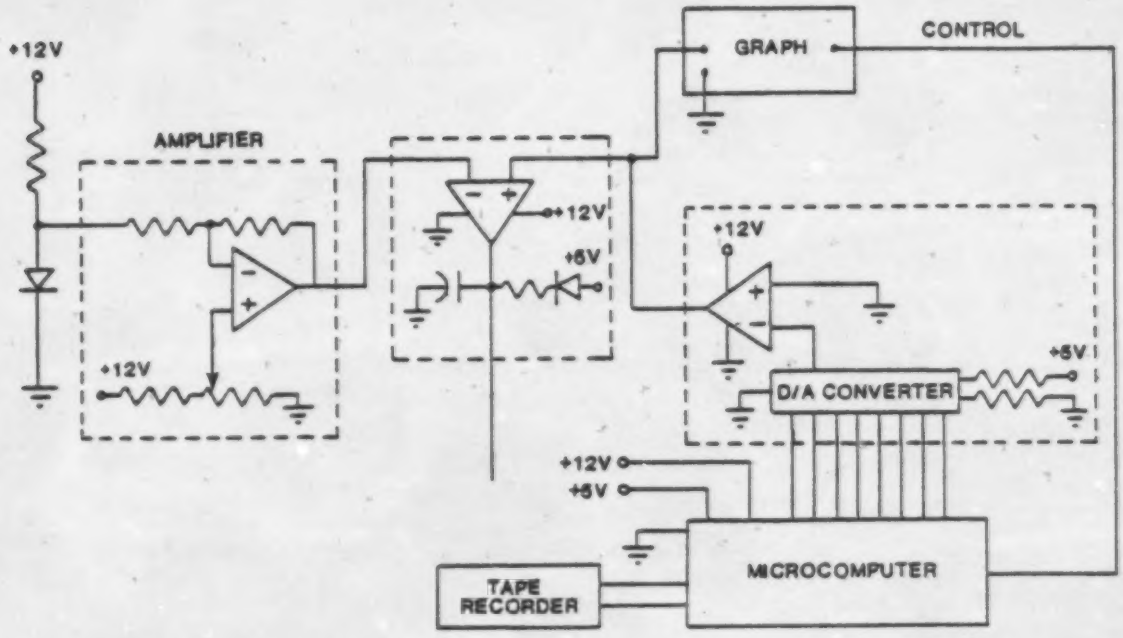
Figure 9. Silicon Diode Probe and Temperature Calibrated Meter.

As temperature changes, the voltage drop across D_1 in the probe also changes. This voltage drop change is sensed

by the temperature circuit and, in turn, provides a d.c. voltage to the monitor temperature meter.

A system similar to the one above – but one in which data can actually be stored and displayed – is shown in Figure 10a.

a. Block Diagram - Temperature Circuitry



b. Actual Circuitry

Figure 10. Temperature Monitor and Record Chart.

Figure 10b shows the circuitry that is used to interface the temperature probe with this tape recorder and graph. With this system, the changing temperature per time is plotted on the graph. The tape recorder is used to record data for future use.

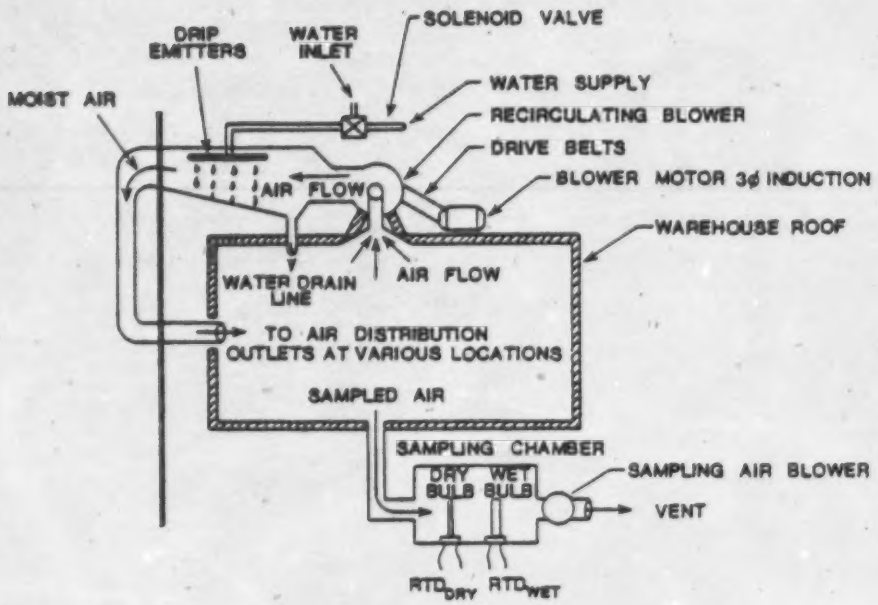
The microcomputer's role is to control the system through an internal program. First, the data from the probe is read a number of times per hour. After the data is read, the microcomputer sends the results to the graph, which is continuously running and recording. The operator periodically receives the graph results from the tape recorder. The cassette tapes can be retained and used for future studies and research. This particular system is presently available using the KIM-1 microcomputer board and associated circuitry.

HUMIDITY CONTROLLER

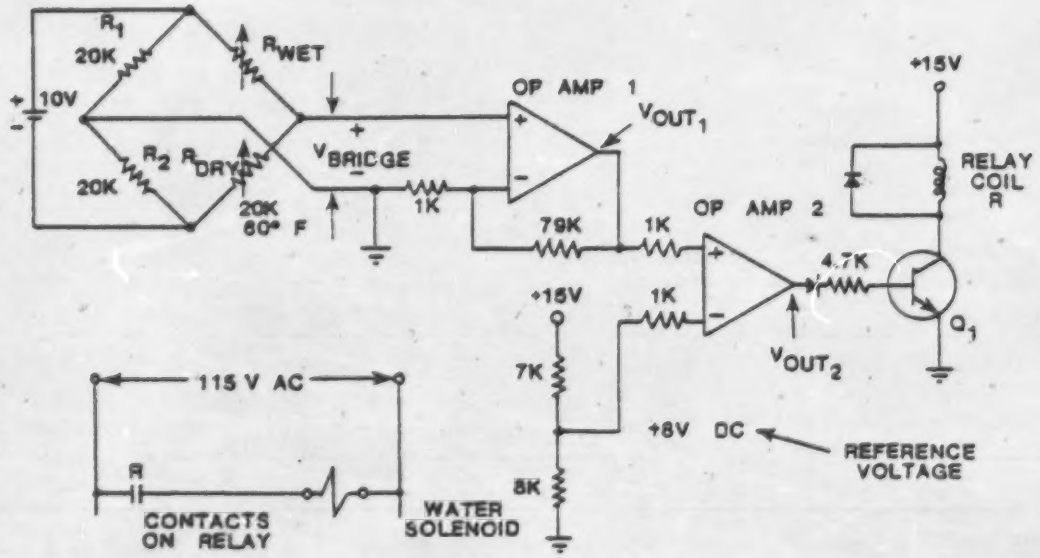
Energy management applications include environmental monitoring and control. Figure 11 displays one method of controlling the relative humidity inside a building.

Figure 11a shows the physical requirements. The air within a building is sampled via a sampling vent which channels air into a wet-dry bulb unit. Depending upon the air "condition" sensed by this unit, a water-inlet solenoid valve is opened, allowing water to be fed to the drip emitters which eject atomized water into the air duct system. Because the air is constantly monitored, the relative humidity can be reasonably controlled.

The wet and dry bulbs inside the sensing unit are wired to the circuit shown in Figure 11b. It is this circuit that



a. Distribution System.



b. Control Circuit.

Figure 11. Humidity Controller.

controls the ON-OFF operation of the water inlet solenoid valve shown at the top of Figure 11a.

The R_{wet} and R_{dry} (wet-dry bulbs) are part of a bridge circuit. Operational amplifier 1 receives its signal voltages from the bridge circuit. As the relative humidity decreases, the bridge becomes more unbalanced, causing the output from the bridge (V_{bridge}) to increase. Op amp 1 amplifies V_{bridge}. This op amp is a non-inverting amplifier which increases the signal about 50-80 times, depending on the choice of the resistors attached to the minus (-) input.

Op amp 2 is a voltage comparator. It compares the voltage on its plus (+) input to the voltage on its (-) input. When the op amp 2 (+) input becomes greater than the voltage on the (-) input, its output causes transistor Q_1 to conduct. The output also activates the coil of relay R, which, in turn, activates the solenoid valve.

This system is designed to keep the humidity from falling below a specified percentage that was chosen previously by the bridge circuit design. Units of this type can be purchased for residential or commercial applications.

LIGHT-SENSING SYSTEM

A system that can be used to track the sun so a solar collector can be rotated on a motor-driven base is shown in Figure 12a.

In Figure 12b, the sun rays, when they strike the surface of the photovoltaic cell, produce a voltage output from the cell. This voltage is used to drive the input of a high gain transistor. The transistor output current activates relay R

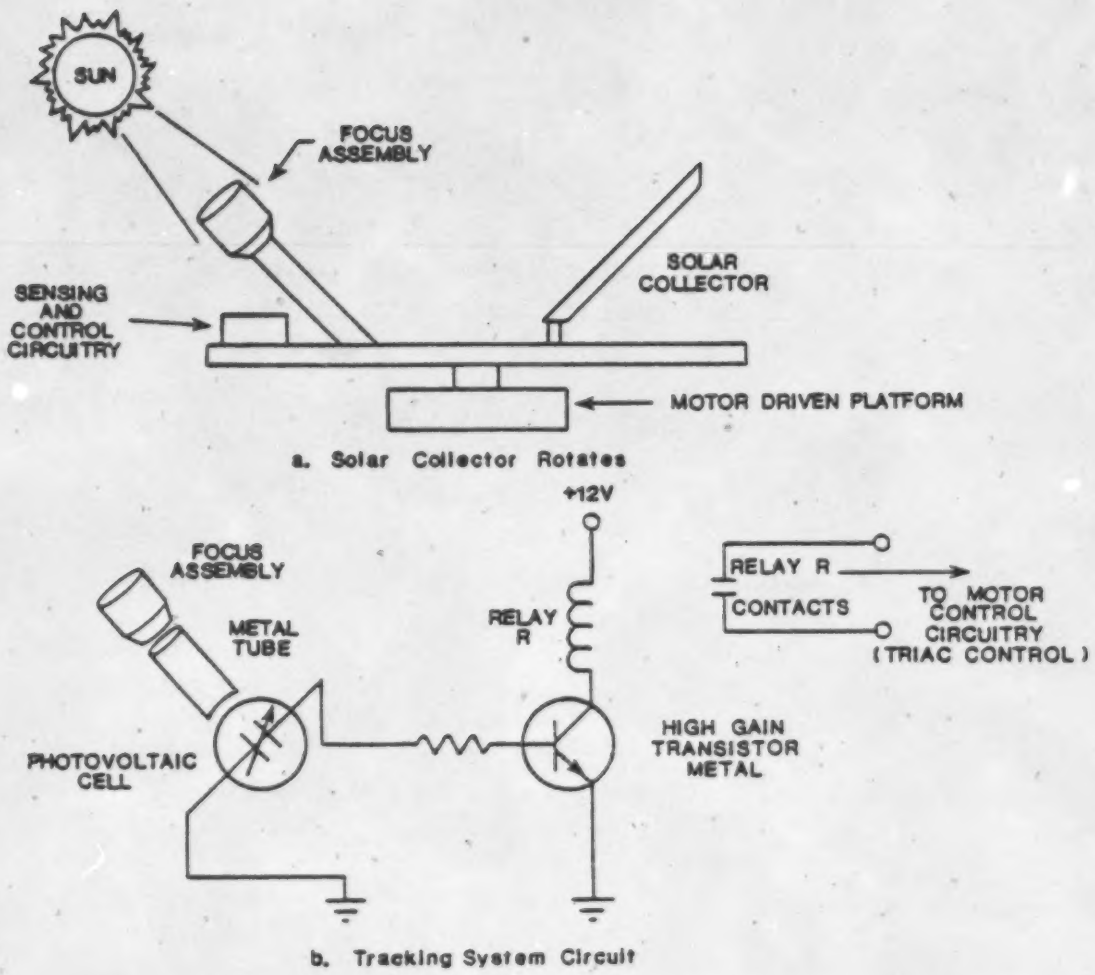


Figure 12. Solar – Sun-Tracking System.

and its associated contacts, which, in turn, send a signal to the motor control circuit to turn off the motor. The motor will, therefore, hunt for the sun until the sun strikes the surface of the cell.

On cloudy days or at night, the system would continue to hunt if additional circuitry to prevent this was not added. A simple circuit not shown here must be incorporated to perform this latter task.

DIGITAL SYSTEMS

Digital systems communicate the same information as analog systems but divide it up into a series of measurements, communicated by means of a binary code. When the number of measurements per any given length of time is greater, the accuracy of the digital representation becomes greater.

The following paragraphs present two examples of basic digital systems.

BINARY COUNTERS

Figure 13 shows a digital or binary counter model 74193. This unit only counts binary numbers, and is capable of counting them as high as 1111_2 (15_{10}). Looking closely, note four data inputs and four data outputs. It also has the ability to count up or down or clear itself and reset to 0000.

Incorporated in this one-piece IC are four J-K flip-flops and several gates that are combined to perform one main function.

The inputs can be connected to switches or electronic digital circuits, and the output can drive four LEDs or other digital circuitry. Figure 14a shows one example of the hook-up.

Note particularly that there is a carry and borrow feature. In any up-down counting sequence (as in mathematical addition and subtraction problems) a carry or borrow may occur. Figure 14b shows the actual pin connection for the 74193 binary counter.

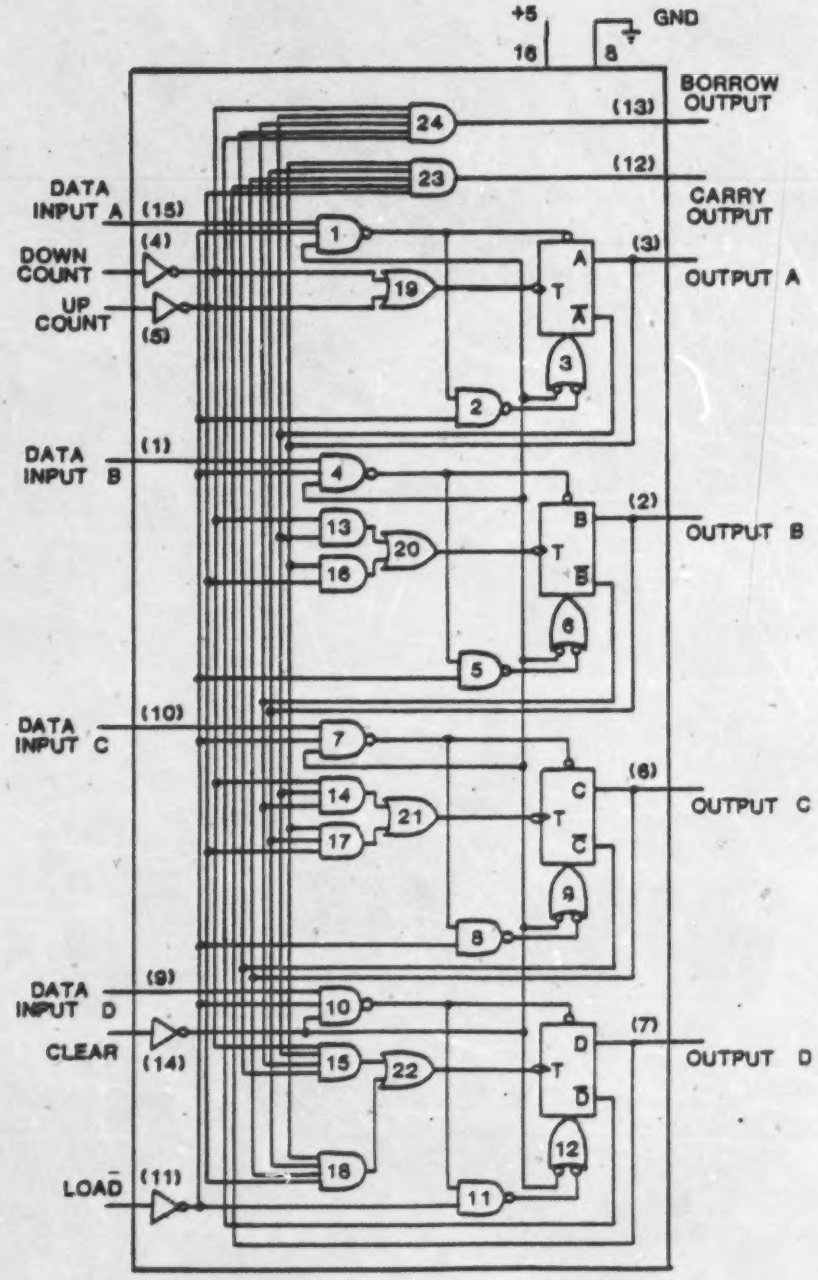
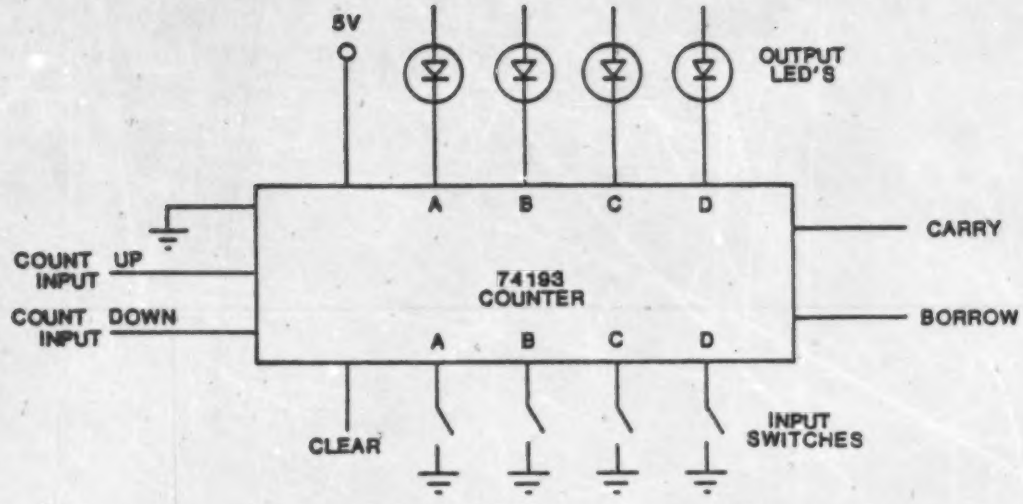
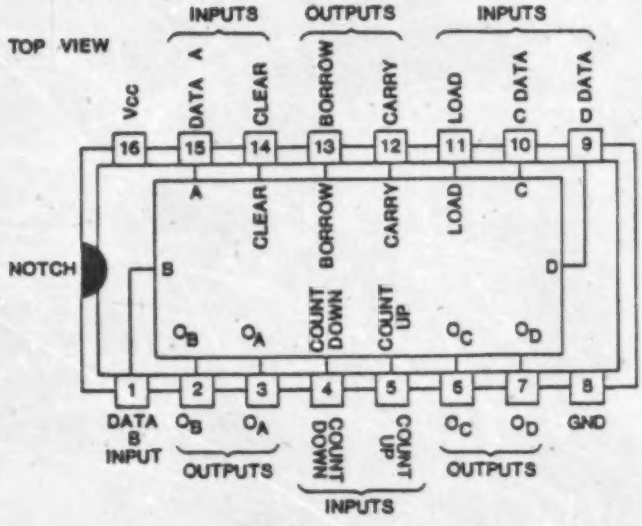


Figure 13. A 74193 Binary Counter System.



a. 4-Bit Counter Application



b. Pin Connections - 74193 Counter

Figure 14. A 4-Bit Binary Counter.

SHIFT REGISTER

In many respects, shift registers are electrically similar to binary counters. However, the individual elements are

wired so that the information stored in one bit location can be shifted to another bit location. Figure 15 shows this concept.

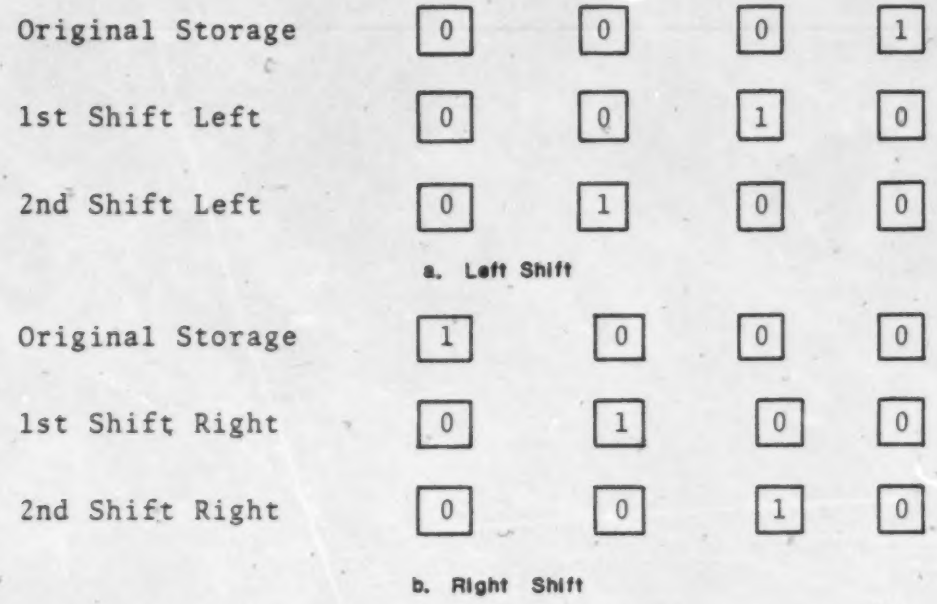


Figure 15. Shift Register Principle (4-Bit).

When a shift left is performed, all bits shift one position to the left. Of course, a right shift causes all bits to shift one position to the right. Figure 16 shows the diagram of a 4-bit IC shift register.

Figure 16 shows that to form this system, four flip-flops are used, as well as several logic gates. The results of the shifts are displayed externally on the added LEDs, L1-L4. The inputs come from serial inputs from other associated external circuitry.

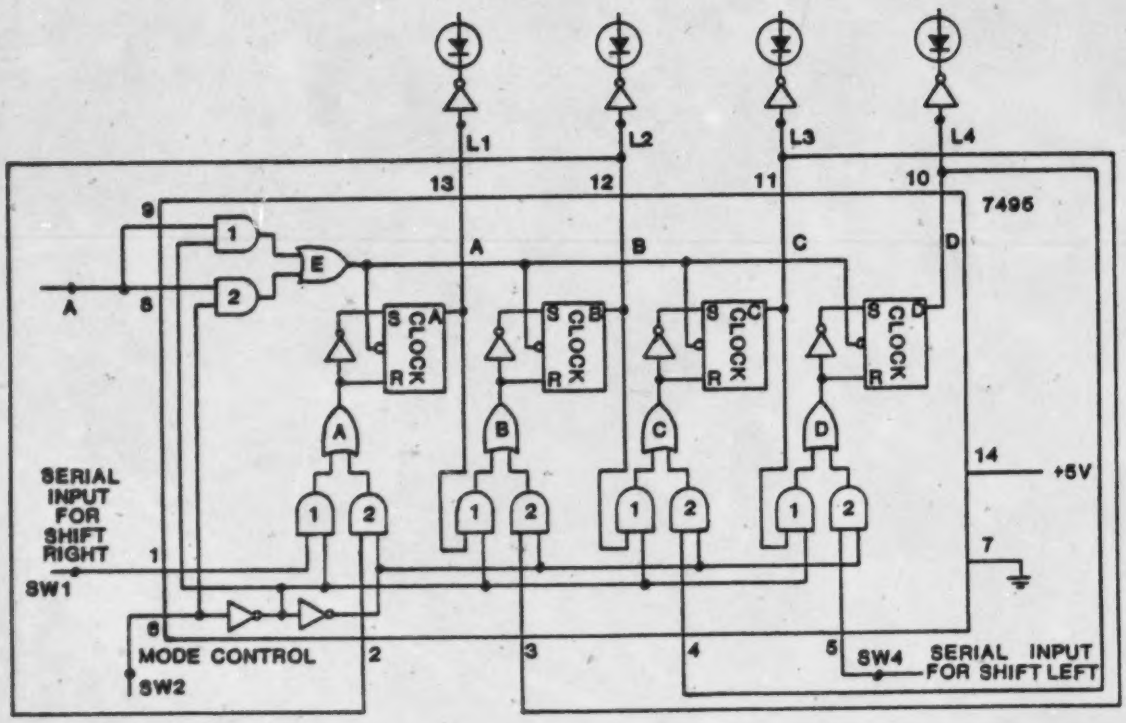


Figure 16. Shift Register Circuit.

EXERCISES

1. Locate a diagram of a small solid-state audio system and determine the following:
   a. What types of transistors are used.
   b. What types of IC stages are used.
2. Locate a diagram of a microcomputer board (Heathkit ET-3400; KIM-1 6502; Motorola D_2 Kit; and so forth), and through research, determine what new IC chips are used and what functions they perform.
3. Research and list the functions of the following IC devices:
   a. Digital decoders (use a 7442 TTL IC BCD to decimal decoder).
   b. Digital multiplexers (use a 74151 multiplexer).

LABORATORY MATERIALS

+5 volt power supply @ 100 mA
Breadboard system for circuit construction
D.C. voltmeter
Components
    1-74193 synchronous binary counter
    2-7476 dual J-K flip-flops

NOTE: The Heathkit ET-3400 digital trainer is one such breadboard system that functions well for the following experiment. It also has the power supply on-board.

LABORATORY PROCEDURES

The objective of this laboratory is to examine the characteristics and operation of a binary counter. A binary counter is categorized as a sequential logic circuit. Its specific uses are timing, sequencing, and storage. As are other sequential circuits, this one has memory capable of storing binary numbers. After this laboratory is completed, note, particularly, the flip-flops used and the timing circuitry.

1. Construct the circuit shown in Figure 17. (Use the 7476 J-K flip-flop chip.) It is actually a binary counter. Do not apply power yet.

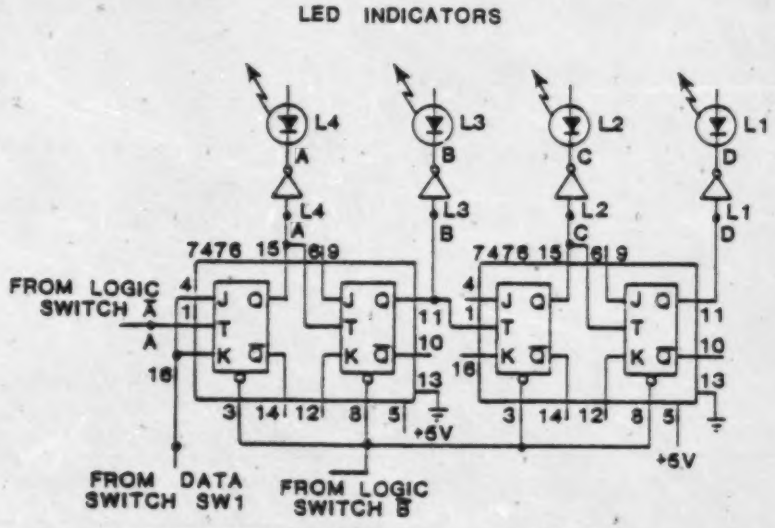


Figure 17. Binary Counter, Using J-K Flip-Flops.

NOTE: Figure 18 shows the pin-out for the 7476 IC.

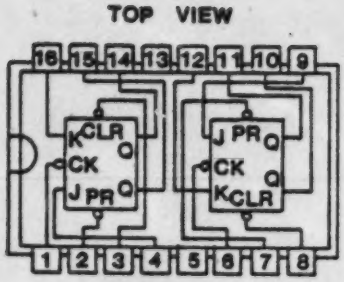


Figure 18. 7476 J-K Flip-Flop Pin Diagram.

2. The following data is necessary before starting:
   a. LEDs are as follows:
      LED A (least significant bit)
      B
      C
      D (most significant bit)
   b. 1. Logic switch $\overline{A}$ will be used to step the counter (timer lead).
      2. Logic switch $\overline{B}$ will be used to reset the counter.
      3. Data switch sw-1 is used to input the counting numbers.
      b. This 4-bit counter can count from 0000 to 1111. Upon reaching one more count past 1111, the counter will trip back to 0000.

   NOTE: Wait until the instructor has checked all wiring before applying power.

3. The counter experiment will begin with the data switch set to binary 1. Now apply power. (Leave sw-1 high.)

4. Record the states of the four LEDs.

   D _____ MSB

   C _____

   B _____

   A _____ LSB

5. Reset the counter by operating logic switch $\overline{B}$. (When operated, a binary 1 will be applied to the reset lead which resets all flip-flops.) When the $\overline{B}$ switch is released, the counter should reset.

6. Record the states of the four LEDs.

   D _____ LSB

   C _____

   B _____

   A _____ MSB

7. Step the counter by operating the logic switch $\overline{A}$. One full operation of this switch should cause the counter to add 1 to the binary counter number. Record this data in the Data Table (column 7a). Continue stepping counter until the number 15 (1111_2) has been reached. Record the data in the Data Table (columns 7b through 7o).

8. Step the counter one more time (logic switch $\overline{A}$). Record LED output in the Data Table.

   Discussion: The counter Data Table should reflect a count in binary from 0000 to 1111, with all intermediate numbers present.

9. Reset timer (logic switch $\overline{B}$).

10. Attach a 1-Hz clock pulse to the logic switch $\overline{A}$ lead. The counter should count automatically. Does it? Before doing so, remove the wire from logic switch $\overline{A}$. Shut off the trainer.

11. Require the circuit to reflect Figure 19.

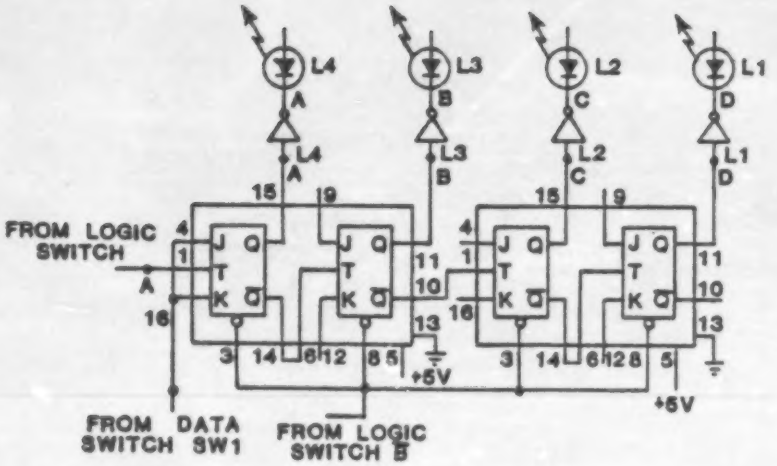


Figure 19. Binary down counter.

NOTE: In this section of the lab, the counter will be set to count down.

12. With sw-1 up (binary 1), apply power, and reset counter by momentarily depressing logic switch $\overline{B}$.
Record the data here and place it in the Data Table as shown.

D _____
C _____
B _____
A _____

13. Step the counting, using logic switch $\overline{A}$ and record the results in the Data Table after each step. Record the decimal number on the right.

14. Does the counter step down? _____

15. Connect a 1-Hz clock pulse to the place where the logic switch $\overline{A}$ is connected. Before doing so, remove the logic switch $\overline{A}$ wire. What happens to the counting?

DATA TABLE

DATA TABLE

		D	C	B	A
(Step 5) Reset	0				
Step 7a	1				
Step 7b	2				
Step 7c	3				
Step 7d	4				
Step 7e	5				
Step 7f	6				
Step 7g	7				
Step 7h	8				
Step 7i	9				
Step 7j	10				
Step 7k	11				
Step 7l	12				
Step 7m	13				
Step 7n	14				
Step 7o	15				
Step 8	0				

Data Table. Continued.

	D	C	B	A	Decimal No.
Step 10					
Step 11					

REFERENCES

Heath Company. Digital Techniques - Heathkit Learning Publications. Benton Harbor, MI: Heath Company, 1978.

Maloney, Timothy J. Industrial Solid-State Electronics – Devices and Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc. 1979.

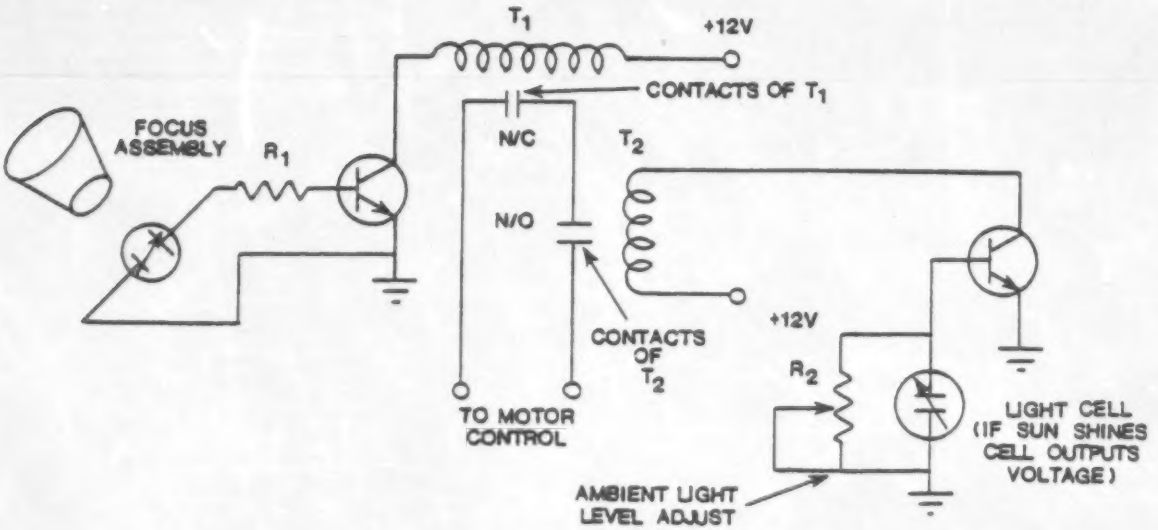
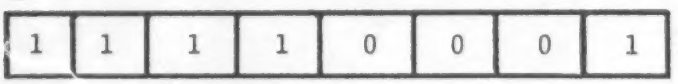
Sams, Howard W. This is Electronics – Circuits and Applications. Indianapolis, IN: Educational Services, Inc. 1970.

TEST

1. Name the five parts of an electronic voltage regulator (discrete or integrated sytem).
   a. _____
   b. _____
   c. _____
   d. _____
   e. _____
2. A d.c. amplifier cannot pass a.c. (True or False) _____.
3. The trigger voltage on an SCR must be _____ to casue it to trigger.
   a. d.c.
   b. a.c.
   c. Neither of the above.
   d. Either of the above.
4. Triacs are used to control ...
   a. d.c. motors.
   b. a.c. motors.
   c. Neither.
   d. Regulators.
5. Thermocouples can measure temperatures accurately from ...
   a. 0-50°F.
   b. 0-220°F.
   c. 50-100°F.
   d. above 200°F.

6. Would the circuit shown below allow the solar tracking system to stop hunting if the sun was behind clouds or if it was dark outside?

   a. Yes.
   b. No.
   c. The T_2 contacts should be N/C.
   d. The motor would burn up.



7. Binary counts can count only in binary directly. How far could an 8-bit counter count? (Start at 0 as the first count.)
   a. 7
   b. 15
   c. 31
   d. 63
   e. 127
   f. 255
8. Shift registers are used to multiply and divide in binary. Looking at the 8-bit register shown below what would the binary number be if the register was shifted right three places?